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STRATEGIES FOR REDUCING POLLUTANTS FROM IRRIGATED LANDS IN THE GREAT PLAINS

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A manual has been prepared which will serve as a planning guide for determining alternative management practices to limit nonpoint source water pollution from irrigated lands in the Great Plains. Section One contains a summary of federal water pollution legislation as it relates to irrigated agriculture. The areal extent and intensity of irrigation in the newly-defined Irrigated Great Plains is given, along with a review of select physical characteristics of the region. Five irrigated crop production areas are broadly delineated. Pollutants in irrigation return flows are identified and described in Section Two. The authors examine the effects of current irrigation management practices on pollution in the return flow. The most probable pollution problems are discussed. In Section Three, various alternative irrigation management options to reduce pollution from irrigation return flows are considered. Specific practices are rated according to their ability to reduce pollutants from surface runoff and deep percolation. In Section Four, the authors discuss the relative degree of economic effects which selected alternative management options could have on both central and southern plains agricultural producers. An analysis is given of seven management options which planners would be likely to consider for policy formulation. Control program strategies for implementing alternative irrigation practices are presented in Section Five. Included is the problem-solving sequence necessary to develop a management program for limiting potential site-specific pollution problems.

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FOREWORD

Environmental protection efforts dealing with agricultural and nonpoint sources have received increased emphasis with the passage of the Clean Water Act of 1977 and the subsequent implementation of the Rural Clean Water Program. As part of this Laboratory's research on the occurrence, movement, transport, fate, impact, and control of environmental contaminants, data and analytical methodologies are developed to assess the causes and possible solutions of adverse environmental effects of irrigated agriculture.

Efforts to achieve water quality goals include the identification and application of best management practices (BMPs) to control agriculturally related water pollutants. This report examines irrigation management practices and how they contribute to water quality degradation arising from the loss of sediments, nutrients and pesticides from irrigated cropland. Alternative irrigation practices are evaluated with respect to their effects upon water quality and the economy of the agricultural producer. Strategies for the development of pollution control programs are described which should be useful in reaching technically sound and economically feasible environmental management decisions. This report should especially benefit environmental planners and managers as they attempt to identify water quality problems and to implement control strategies to alleviate those problems in the irrigated Great Plains.

Clinton W. Hall

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ABSTRACT

A manual has been prepared which will serve as a planning guide for determining alternative management practices to limit nonpoint source water pollution from irrigated lands in the Great Plains. The manual has five independent yet integrated sections, intended to assist agency personnel and others in formulating areawide management plans for irrigation practices.

Section One contains a summary of federal water pollution legislation as it relates to irrigated agriculture. The areal extent and intensity of irrigation in the newly-defined Irrigated Great Plains is given, along with a review of selected physical characteristics of the region. Five irrigated crop production areas are broadly delineated in this introductory section.

Pollutants in irrigation return flows are identified, defined, and described in Section Two. The authors then examine the effects of current irrigation management practices on pollution in the return flow that results from surface runoff and deep percolation. The most probable pollution problems in the Irrigated Great Plains are discussed.

In Section Three, various alternative irrigation management options to reduce pollution from irrigation return flows are considered. Specific practices are rated according to their ability to reduce pollutants from surface runoff and deep percolation.

In Section Four, the authors discuss the relative degree of economic effects which selected alternative management options could have on both central and southern plains agricultural producers. An analysis is given of seven management options which planners would be likely to consider for policy formulation. The economic effects associated with each of these options are examined.

Control program strategies for implementing alternative irrigation practices are presented in Section Five. Included is the problem-solving sequence necessary to develop a management program for limiting potential site-specific pollution problems. Examples of two different types of return flow problems in the Great Plains are used to illustrate and assess potential solutions to deep percolation and surface water runoff.

This report was submitted in fulfillment of Grant No. R-805249 to the Nebraska Water Resources Center, University of Nebraska--Lincoln under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of October 1, 1977, to August 31, 1979, and work was completed as of February 15, 1980.

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Section Three. Available On-Farm Irrigation Management Alternatives for Reducing Pollution From Irrigation Return Flows
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Section Four. Economic Feasibility of Farm Management Alternatives to Reduce Pollution
by R. J. Supalla and R. R. Lansford

Section Five. Control Program Strategies for Irrigation Return Flows
by J. R. Gilley and M. Twersky

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SECTION 1

IRRIGATION IN THE GREAT PLAINS--AN OVERVIEW

by
M.-L. Quinn

INTRODUCTION

This manual is to serve as a guide for determining alternative management practices intended to reduce nonpoint source water pollution which may result from irrigated agriculture in the Great Plains. While the personnel of water planning agencies are considered the manual's principal audience, it also may be of assistance to farmers, along with others whose work is related to the impact irrigated agriculture may have on water quality.

Farmers have been irrigating fields in the Great Plains since the 1860's (Borrelli, 1979) so it is reasonable to ask the question: why at this particular time has a manual been written on alternative irrigation management practices? Following are the three principal reasons for the creation of this volume:

(1) Currently, more and more people throughout the Great Plains are having to make planning decisions and establish guidelines pertaining to water quality. This surge of activity stems largely from programs begun as a result of Public Law (P.L.) 92-500, the "Federal Water Pollution Control Act Amendments of 1972," passed by Congress in October 1972.

(2) The dominant economic activity in the Great Plains is agriculture. In 1974, the U.S. Department of Agriculture classified 62 million hectares in the region's ten states as cropland used for crops (U.S. Dept. of Agr., 1978). Of this amount, an estimated 12 million hectares, or roughly 19.5 percent, were irrigated as of 1978 (*Irrigation Journal*, 1978). Thus, irrigation agriculture is one of the avenues for human impact on water quality in the Great Plains, being more significant in some areas than others.

(3) In many instances, personnel from local, state, and regional resource agencies do not have the expertise in irrigation practices which is now needed. Thus, these agencies are at a disadvantage as they strive to comply with the requirements of federal legislation concerning nonpoint source pollution as related to irrigated agriculture.

The objective of this project was to "produce a manual providing technical guidance on the best available practices for controlling nonpoint pollution associated with irrigation agriculture in the Central Plains"

(Hall, 1977).[1/] In addition, there were three results which this undertaking was expected to produce:

> "(1) a state-of-the-art analysis and evaluation of current irrigation practices in light of their effects on water pollution, showing the extent and magnitude of the pollution problem from irrigation;
>
> (2) considerations and evaluation of management alternatives to these current practices, as well as resulting improvements in water quality;
>
> (3) development of a proposed strategy for implementation of these alternatives" (Hall, 1977).

The manual contains five sections, plus appendices. Section One presents a summary of pertinent legislation and important physical characteristics of the Great Plains region. The next three sections elaborate on:

- -- irrigation return flow and how it is affected by agricultural management practices (Section 2)
- -- available on-farm irrigation management alternatives (Section 3)
- -- economic feasibility of farm management alternatives (Section 4).

Then in Section 5, guidance is given on the selection of appropriate management systems. The appendices at the end of the manual contain further detailed information for the reader's reference.

Statement of Philosophy

As one moves from the regional to the state and county levels, and then to the individual farm, the seeming homogeneity of the Great Plains quickly disappears. There is, in fact, a wide range of soil types, subsurface geology, rainfall conditions, water chemistry, and water availability, all of which have helped create a truly heterogeneous physical system. Upon this physical system, man has superimposed his own pattern of crops and agricultural practices.

This complexity makes it impractical to suggest a single agricultural management procedure--for the entire region, for a state within the region, or even for one county--that could be expected to lessen any negative effects which irrigation might have on water quality. (Even a management directive

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[1/] Subsequent to the writing of the proposal by Dr. Hall, it was decided to focus the study on the Great Plains, rather than the Central Plains.

to stop all irrigated agriculture in the Great Plains--an unlikely extreme--probably would not eliminate the problem.) Thus, most management practices intended to reduce nonpoint pollution from irrigation will be site-specific. Assuming, however, that irrigated agriculture is going to continue in the Great Plains, there are some management tools which, when modified to reflect particular local conditions, can ease the impact in the existing problem areas or reduce the development of future problem areas.

Introduced in the manual is a procedure for developing control programs where there is the potential for nonpoint source pollution from irrigated agriculture. While every site will differ, there are a number of common components within the natural and man-made systems which, working together in various combinations, will contribute to a site being more (or less) prone to irrigation-induced nonpoint pollution.

This manual should become the standard guide in the development of management alternatives to limit nonpoint source pollution from irrigated agriculture within the Great Plains. The specific manner in which these alternatives are modified and used, however, will vary from state to state, agency to agency, and individual to individual.

SUMMARY OF PERTINENT LEGISLATION

Concern for water pollution is not new, nor is legislation to deal with the problem. Section 13 of the Rivers and Harbors Act of 1899 (The Refuse Act) is often cited as one of the first federal laws to address the pollution of waters. This law, however, was seldom enforced (Warnick, 1977).

The Federal Water Pollution Control Act of 1948 (P.L. 80-845) was a major step forward. In keeping with past policy, this law recognized "the primary responsibilities and rights of the States in controlling water pollution,..." Public Law 80-845 has been amended and expanded by the following acts:

Water Pollution Control Act Amendments of 1956
Federal Water Pollution Control Act Amendments of 1961
Water Quality Act of 1965, P.L. 89-234
Clean Waters Restoration Act of 1966, P.L. 89-753
Water Pollution Control Amendments of 1972, P.L. 92-500
Clean Water Act of 1977, P.L. 95-217.

The creation of the U.S. Environmental Protection Agency (EPA) in 1970 must also be included as an important, related event because that agency was then placed in charge of the federal government's water pollution programs (Warnick, 1977).

As far as nonpoint source pollution from irrigated agriculture is concerned, P.L. 92-500 (passed in 1972) and P.L. 95-217 (passed in 1977), are particularly significant. The 1972 law, which is administered by the EPA, contains the following definition under Section 502:

> "The term 'pollution' means the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water."

This law also contains the frequently-referenced Section 208 entitled, "Areawide Waste Treatment Management." Section 208 specifies:

- -- that the states prepare plans for areawide waste treatment management;
- -- that these plans contain alternatives for such management;
- -- that the plans be applicable to all wastes generated within a designated area.

Regarding nonpoint source pollution from irrigated agriculture, this same section of P.L. 92-500 goes on to say:

> "Any plan prepared under such process shall include, but not be limited to -- [(A) through (E)]
>
> (F) a process to (i) identify, if appropriate, agriculturally and silviculturally related nonpoint sources of pollution, including runoff from manure disposal areas, and from land used for livestock and crop production, and (ii) set forth procedures and methods (including land use requirements) to control to the extent feasible such sources;..."

In December, 1977, Congress passed the Clean Water Act (P.L. 95-217) which amends item (F) from Section 208 quoted above to read as follows:

> "(F) a process to (i) identify, if appropriate, agriculturally and silviculturally related nonpoint sources of pollution, including return flows from irrigated agriculture, and their cumulative effects, runoff from manure disposal areas, and from land used for livestock and crop production,..."

The new wording is underscored.

In addition, the 1977 law adds to Section 402 of P.L. 92-500 a paragraph stating that no permit, neither federal or state, shall be required for "discharges composed entirely of return flows from irrigated agriculture." By making it clear that return flows from irrigated agriculture were to be regarded as nonpoint sources of pollution and by stating specifically that such flows did not require permits (as did point sources), the way was then open for more defined efforts to deal with this particular problem. Each state's plan must now recommend those regulatory programs considered necessary to reduce or prevent pollution from irrigated agriculture.

There is another important distinction regarding nonpoint sources of pollution (hence, return flows from irrigated agriculture). Management practices to curtail nonpoint source pollution are to be tailored to the uniqueness of the area where the problem exists (Minton, et al., 1978). In other words, the EPA, in its enforcement of these laws, recognizes geographical differences and suggests a site-specific approach. In contrast, point sources of pollution must adhere to a fixed set of effluent standards which is applied nationwide.

Section 35 of the Clean Water Act of 1977 made one further important addition to Section 208 in the 1972 law. It authorized the Soil Conservation Service to "administer a program to enter into contracts...of not less than five years nor more than ten years with owners and operators having control of rural land for the purpose of installing and maintaining measures incorporating best management practices to control nonpoint source pollution for improved water quality..." In addition, the federal government agreed to provide technical assistance in carrying out these management practices and also to share up to 50 percent of their total cost.

As a result of these various pieces of legislation, nonpoint source pollution from irrigated agriculture is the focus of much attention at the state level and has been for several years. This manual is intended to assist the personnel of the numerous state agencies in the Great Plains in making decisions on this subject, for inclusion in their management plans.

THE GREAT PLAINS: ITS WATER, IRRIGATION, AND CROPS

Definition

Traditionally, the Great Plains of the United States has been defined as that region which lies between the Rocky Mountains on the west and the prairies on the east, reaching from Texas to the Canadian border (Thornthwaite, 1936). It includes portions of ten states: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, New Mexico, Colorado, Wyoming, and Montana (Figure 1). Low rainfall, relatively flat terrain, few trees, and a gradual increase in elevation from east to west are four characteristics which make the Great Plains a distinct geographic unit and which set it apart from the rest of the United States.

For the purposes of this manual, however, a further refinement of these physiographic and political boundaries has been necessary. Thus, within the ten states of the traditional Great Plains, there has been delineated the 'Irrigated Great Plains' (Figure 1). As will be explained in a moment, this large expanse of land (some 1,500,000 square kilometers) includes a few areas generally not regarded as plains.

Determination of the size and extent of this particular region was based primarily on the number of irrigated hectares per county in the ten states. The number of irrigated hectares in Montana, Wyoming, Colorado, Nebraska, Kansas, and New Mexico were obtained from the 1976 Agricultural Statistics compiled by the Agriculture Department Crop and Livestock Reporting Service in each state. For North Dakota, 1977 data from the state's Extension Service were used. Information for Oklahoma was derived from a

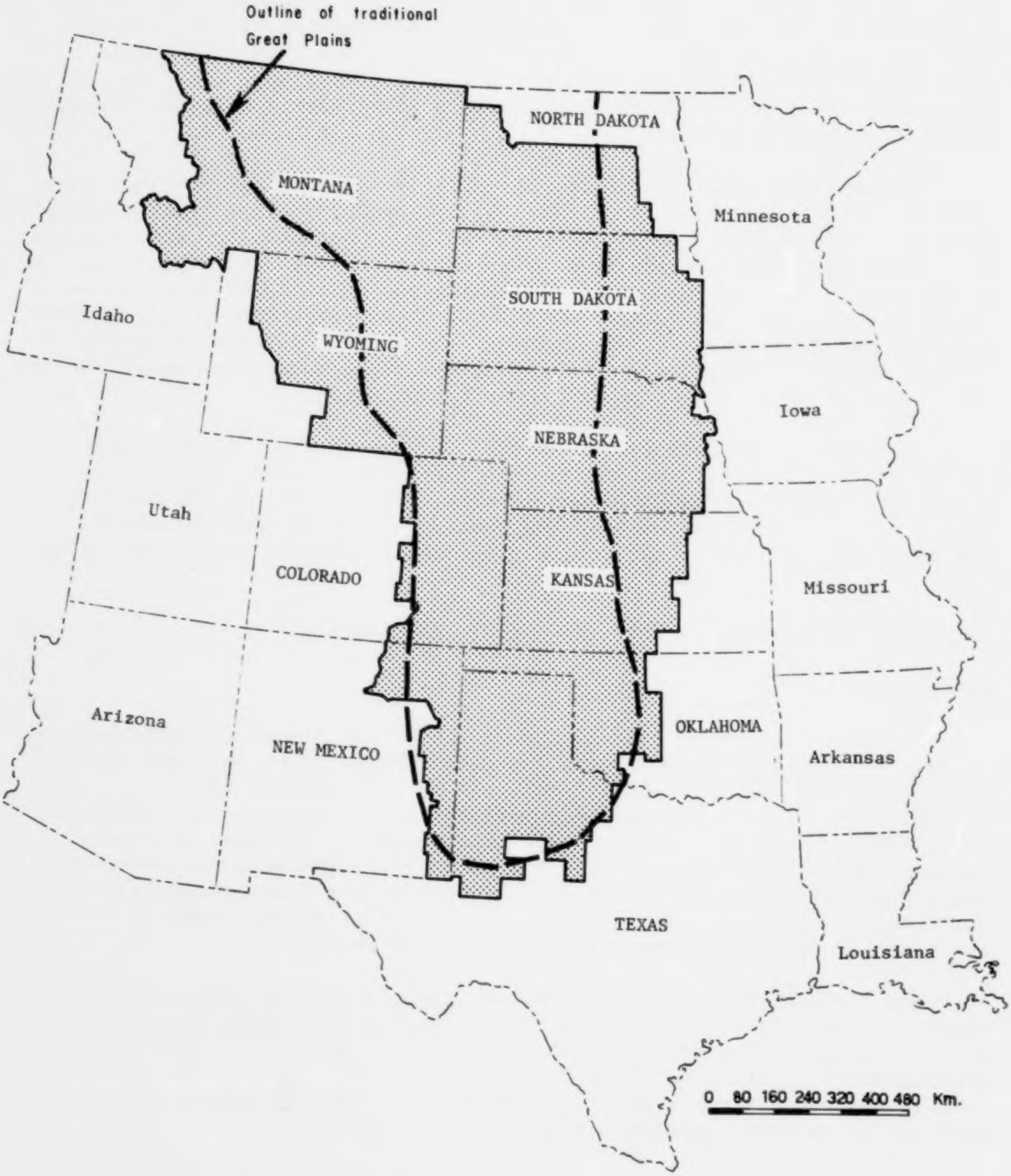

Outline of traditional Great Plains
MONTANA
NORTH DAKOTA
Minnesota
SOUTH DAKOTA
Idaho
WYOMING
Iowa
NEBRASKA
Utah
COLORADO
KANSAS
Missouri
Arizona
NEW MEXICO
OKLAHOMA
Arkansas
TEXAS
Louisiana
0 80 160 240 320 400 480 Km.

Figure 1. The traditional Great Plains and the larger Irrigated Great Plains, as the latter term is used in this manual.

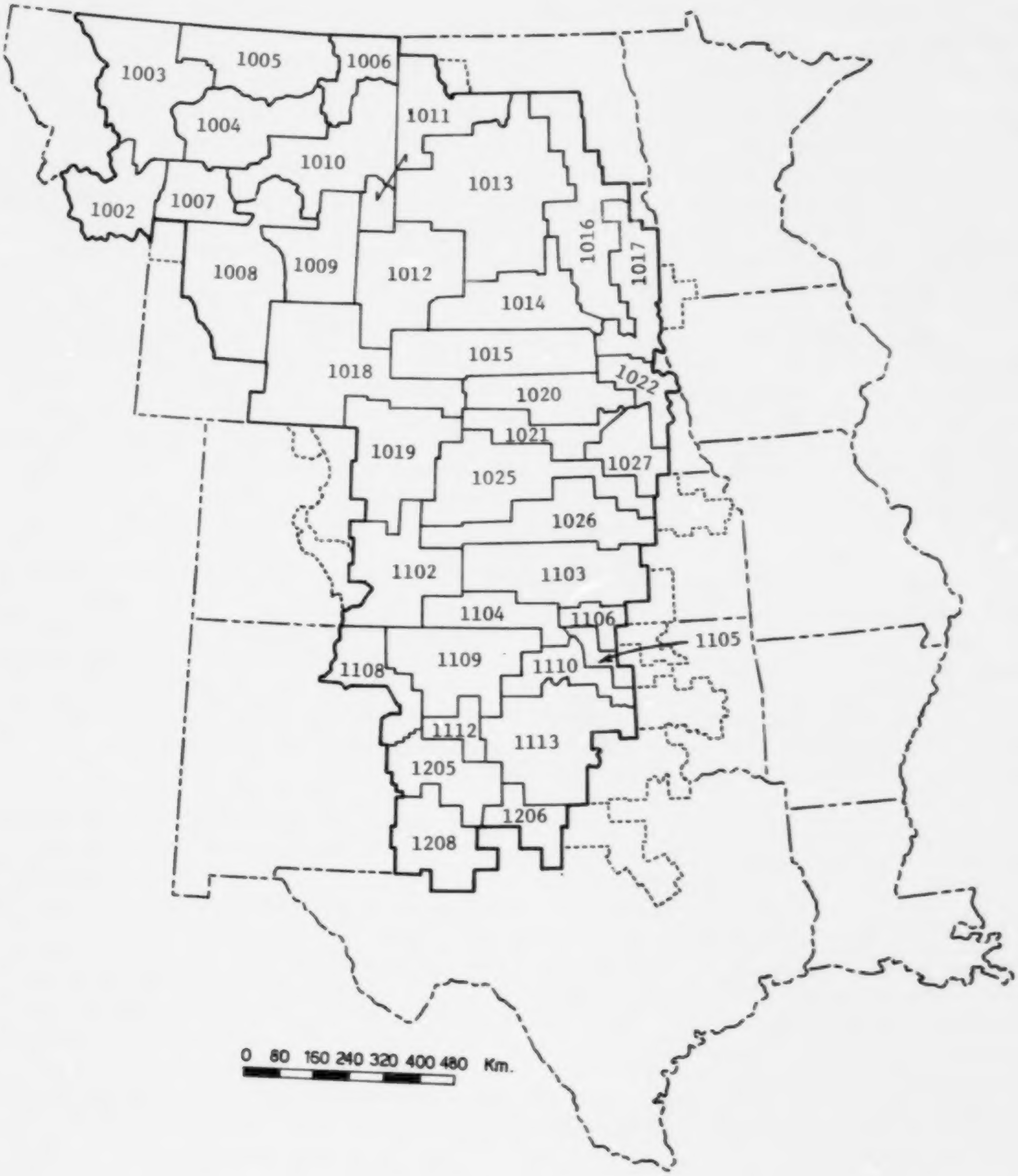
1977 Irrigation Survey prepared by the Oklahoma State University Extension Service. In the case of Texas, it was decided to include in this study only the northern part of the state. County data were obtained from the 1976 Agricultural Statistics, in conjunction with the 1976 High Plains Irrigation Survey. The state of South Dakota no longer compiles figures for irrigated hectares on a county basis. Thus, it was necessary to use the county data from the U.S. Agricultural Census for the year 1974. As a result, what is thought to have been a considerable increase in irrigation in South Dakota during the 1976-1977 drought (R. Beyer, per. com.) is not reflected here. Information on irrigated hectares for all ten states was cross-checked with other sources wherever possible.

County size in the ten Great Plains states varies widely, ranging from 105,000 hectares (Clay County, South Dakota) to 2,358,500 hectares (Fremont County, Wyoming). For this reason, a minimum number of irrigated hectares per county could not be used to determine what counties should be included in the Irrigated Great Plains. As much as possible, the major criterion used was the number of irrigated hectares as a percent of total hectares in each county--the minimum percent being a matter of judgment. Also considered was the amount of total cropland under irrigation in the individual counties.

Based on computations developed for this manual, 28 counties in the Irrigated Great Plains have less than 0.1 percent of their areas under irrigation. The bulk of the lightly-irrigated counties lies in North and South Dakota. In large part, these counties were included for physiographic reasons and for areal consistency. All 416 counties in the Irrigated Great Plains and their respective percentages are listed in Table A-1 in Appendix A. (While the figures listed in Table A-1 were compiled with much care, they are subject to some error and should be used accordingly.)

Also listed in Table A-1 are figures showing total hectares of cropland in each county, along with the percent of that cropland which is irrigated. (The definition of 'cropland' is the same as that used by the U.S. Department of Agriculture in the 1974 Agricultural Census, which defines cropland as: "land from which crops were harvested or hay was cut; land in orchards, citrus groves, vineyards, and nursery and greenhouse products; land used only for pasture or grazing; land in cover crops, legumes, and soil improvement grasses; land on which all crops failed; and land in cultivated summer fallow. It also includes cropland that is idle.") In some counties such as Beaverhead County, Montana and Park County, Wyoming, a high percentage of total cropland is irrigated. Yet, it may represent only a small percent of the county's total area. Instances of this nature were evaluated on a case-by-case basis.

The county information was then organized into larger geographic divisions known as subareas, defined by the U.S. Water Resources Council of the Department of Interior (U.S. Water Resources Council, 1970). While based on river basins, the boundaries of these subareas follow county lines but, in some cases, cross over state lines (Figure 2). For example, Subarea 1025 represents the drainage basin of the Republican River and is composed of 12 counties in Nebraska, 3 counties in Colorado, and 10 counties in Kansas.


1003
1005
1006
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1011
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1016
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1103
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1106
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1108
1110
1112
1113
1205
1206
1208
0 80 160 240 320 400 480 Km.

Figure 2. Subareas of the Irrigated Great Plains, based on river drainage. Dashed lines show excluded parts of subareas.

Data organization focusing on drainage basins provides a useful geographic component to this manual on alternatives for managing nonpoint source pollution from irrigated agriculture. Appendix Table A-2 is a list of all 37 subareas used, and the drainage basin each represents.

It must be emphasized that sections of several states included within the Irrigated Great Plains are a marked departure from the traditional interpretation of the Great Plains. Western Montana is one example. The amount of irrigation in a number of western Montana counties warranted their inclusion, even those in Subarea 1002, which is quite mountainous (G. Westesen, per. com.).

The Bighorn Basin, nestled on the west side of the Big Horn Mountains in northcentral Wyoming, represents the other major departure. As in the case of western Montana, the number of irrigated hectares in the counties of Park, Big Horn, Hot Springs, Washakie, and Fremont warranted the inclusion of this section of Wyoming. Furthermore, the Bighorn Basin is regarded as a potential troublespot for irrigation-related water quality problems (Bill Long, per. com.).

When a subarea extended into a sector where there were comparatively few irrigated hectares, the counties in that part of the subarea were excluded from the study. (The exception of major parts of the Dakotas has already been mentioned.) This was the case for Subareas 1011, 1018, 1019, 1027, 1102, 1103, 1105, 1106, 1110, 1113 and 1206. The excluded portions of these subareas are shown by dashed lines in Figure 2. The Iowa and Minnesota portions of Subarea 1017 also were excluded, as was Yellowstone National Park from Subarea 1008.

In the Irrigated Great Plains as a whole, there are roughly nine million hectares under irrigation (see Tables 4 and 5). Figure 3 gives an overview of where this irrigation is located in the region. The distribution used in this map was determined by calculating the percent of irrigated hectares per total hectares in each subarea. For example, there are 5,922,000 hectares in Subarea 1025, of which 628,000 hectares are irrigated--that is, 10.6 percent. (These 628,000 irrigated hectares represent roughly 19 percent of the total cropland in that subarea.) The largest percentage of irrigated land is in Subarea 1205 (Brazos headwaters), where 38 percent of the subarea's 3,381,000 total hectares are under irrigation. The irrigation densities for all the subareas are listed in Table 1, along with figures for total cropland in each subarea and the percentage of that cropland which is irrigated.

It is not surprising that within Subarea 1205 is located the most intensively irrigated county in all the Irrigated Great Plains. This is Hale County, Texas, with 77 percent of its total area irrigated. Those counties having 50 percent or more of their total area under irrigation are listed in Table 2.

North and South Dakota stand out in Figure 3 as having little irrigation. Only a handful of counties in the two states have over 1 percent of their total area irrigated, and many are under 0.5 percent. It is important

TABLE 1. PERCENT IRRIGATED OF EACH SUBAREA WHICH LIES WITHIN THE IRRIGATED GREAT PLAINS, ALONG WITH PERCENT IRRIGATED OF EACH SUBAREA'S TOTAL CROPLAND

Subarea	Percent of subarea irrigated	Total hectares in subarea 1/ (1,000)	Cropland in subarea Total hectares 2/ (1,000)	Cropland in subarea Percent irrigated 3/
1205	38 %	3,381	2,022	64.0%
1021	29	1,955	962	60.0
1112	28.7	1,092	504	62.0
1027	26.7	2,192	1,681	34.8
1104	16.6	2,455	1,351	30.0
1109	16.6	4,788	1,508	59.4
1022	11.5	1,675	1,290	15.0
1025	10.6	5,922	3,275	19.0
1208	10.5	3,747	1,053	37.3
1103	9.7	5,316	3,679	14.0
1020	8.2	3,465	999	28.5
1019	7.6	5,036	2,059	18.7
1018	6.1	7,935	676	71.0
1015	4.4	4,890	1,070	20.0
1002	4.0	3,431	277	49.0
1113	3.5	6,259	2,384	9.2
1102	3.3	4,898	762	21.0
1007	3.0	2,157	245	26.4
1008	3.0	7,389	310	71.0
1026	2.6	4,480	2,402	5.0

(Continued)

TABLE 1. (Continued)

Subarea	Percent of subarea irrigated	Total hectares in subarea (1,000) [1]	Cropland in subarea: Total hectares (1,000) [2]	Cropland in subarea: Percent irrigated [3]
1003	2.3%	6,191	1,872	7.7%
1110	2.0	2,089	645	6.7
1105	1.7	820	386	4.0
1009	1.6	3,820	175	34.4
1010	1.6	5,471	764	11.4
1108	1.6	2,775	155	28.5
1105	1.2	4,503	1,034	5.3
1017 [4]	1.2	3,228	2,399	3.2
1206	1.1	1,891	619	3.4
1004	0.9	4,329	500	8.0
1012 [4]	0.7	5,309	456	8.3
1011	0.6	4,297	1,566	1.5
1006	0.5	2,100	1,008	1.0
1106	0.4	936	470	0.8
1016 [4]	0.3	5,540	3,804	0.5
1014 [4]	0.2	4,245	1,244	0.7
1013 [4]	0.2	9,911	3,896	0.5

---

[1] When the entire subarea was not included in the Irrigated Great Plains, the size given here is for the included portion only.

[2] Based on figures from the 1974 Census of Agr., (for each of the ten states in this study) U.S. Dept. of Commerce, Bureau of the Census.

[3] This percent was obtained by taking 1976-1977 figures for irrigated hectares (1974 figures for So. Dak.) and dividing them by 1974 U.S. Dept. of Commerce Census of Agr. figures for total cropland. As total cropland is fairly stable from year to year, any error introduced by this procedure

would be slight. As noted in the text, the one exception would be subareas involving South Dakota counties.

[4] These subareas include counties in South Dakota. Thus, the figures related to irrigated hectares are based on 1974 U.S. Census of Agriculture data and thereby thought to be somewhat low.

TABLE 2. COUNTIES IN THE IRRIGATED GREAT PLAINS WITH 50 PERCENT OR MORE OF THEIR TOTAL HECTARES IN IRRIGATION

County	State	Percent of county irrigated	Total hectares in county (1,000)	Percent of county's total cropland which is irrigated	Subarea No.
Hale	Texas	77.6 %	253.7	84.8 %	1205
Palmer	Texas	66.5	222.6	82.0	1205
Castro	Texas	66.3	227.8	84.6	1205
Lamb	Texas	66.0	264.7	95.0	1205
Hamilton	Nebraska	64.5	139.2	74.0	1027
Hansford	Texas	60.9	234.7	100.0	1109
Haskell	Kansas	56.6	150.1	67.0	1104
Phelps	Nebraska	55.0	140.8	71.0	1021
Merrick	Nebraska	53.4	124.2	79.0	1021
Hall	Nebraska	53.0	139.2	78.0	1021
York	Nebraska	52.5	149.3	63.3	1027
Lubbock	Texas	52.3	231.5	63.8	1205
Swisher	Texas	50.6	231.9	73.0	1112

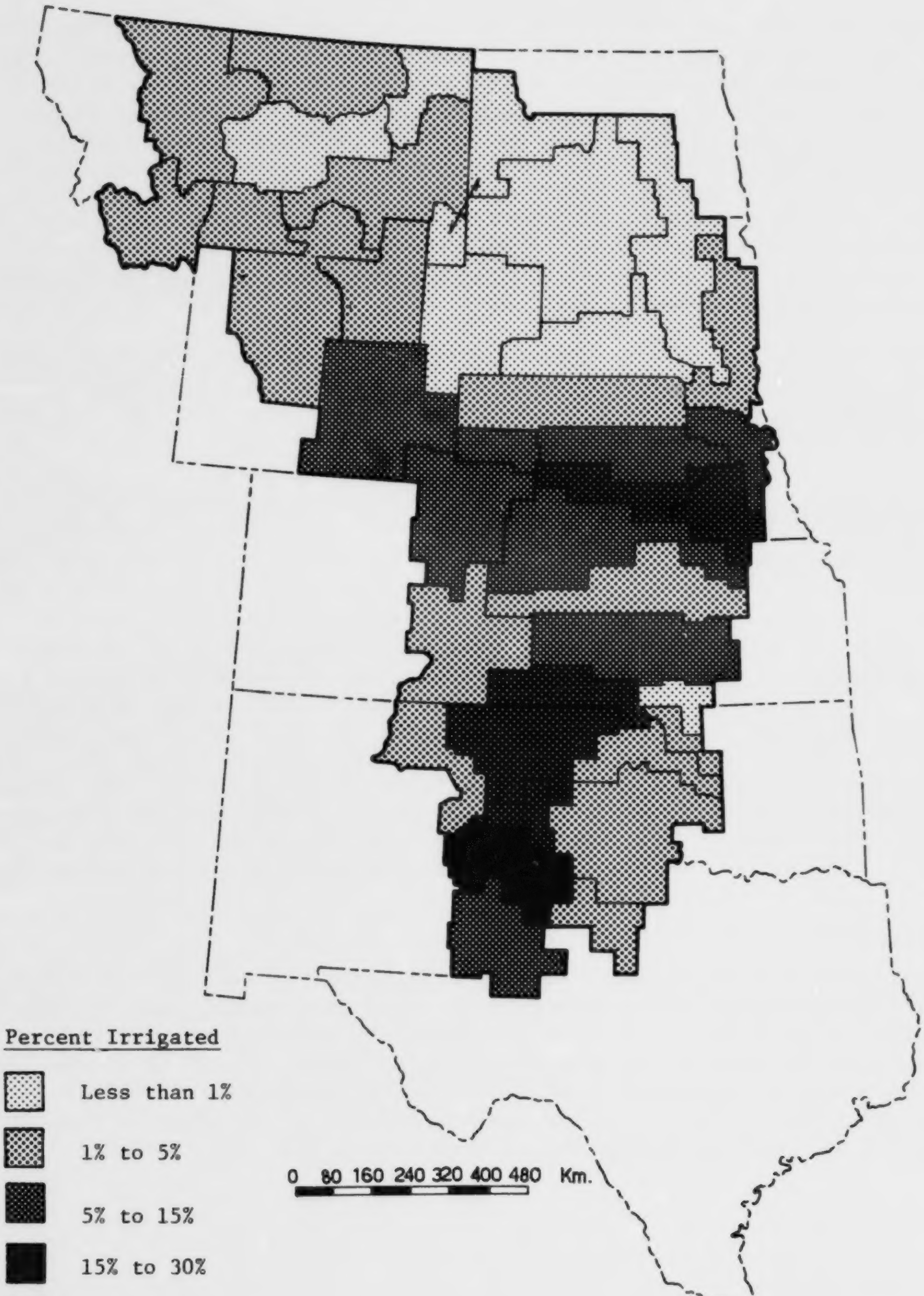

Percent Irrigated
Less than 1%
1% to 5%
5% to 15%
15% to 30%
30% or more
0 80 160 240 320 400 480 Km.

Figure 3. Distribution of irrigation density throughout the Irrigated Great Plains, based on irrigated hectares per total hectares in each subarea.

to point out, however, that within any of the lightly-irrigated subareas, there may be small sections where irrigation is quite concentrated. The 23,000 irrigated hectares of the Belle Fourche Project in South Dakota's Butte County, located in Subarea 1012 (Cheyenne River drainage), is an example (J. Wiersma and D. Wilde, per. com.). Thus, the densities of irrigation shown in Figure 3 do not imply, a priori, that nonpoint source pollution does or does not occur in certain parts of the Irrigated Great Plains. A water quality problem related to irrigated agriculture can develop at any given location if there exists a particular combination of soil conditions, climatic factors, cropping patterns, irrigation systems, and agricultural management practices.

The subareas of most intensive irrigation shown in Figure 3 largely overlie the Ogallala aquifer (Figure 4). The major exception is the included portion of Subarea 1027, which is the drainage basin of the Big Blue River in Nebraska.

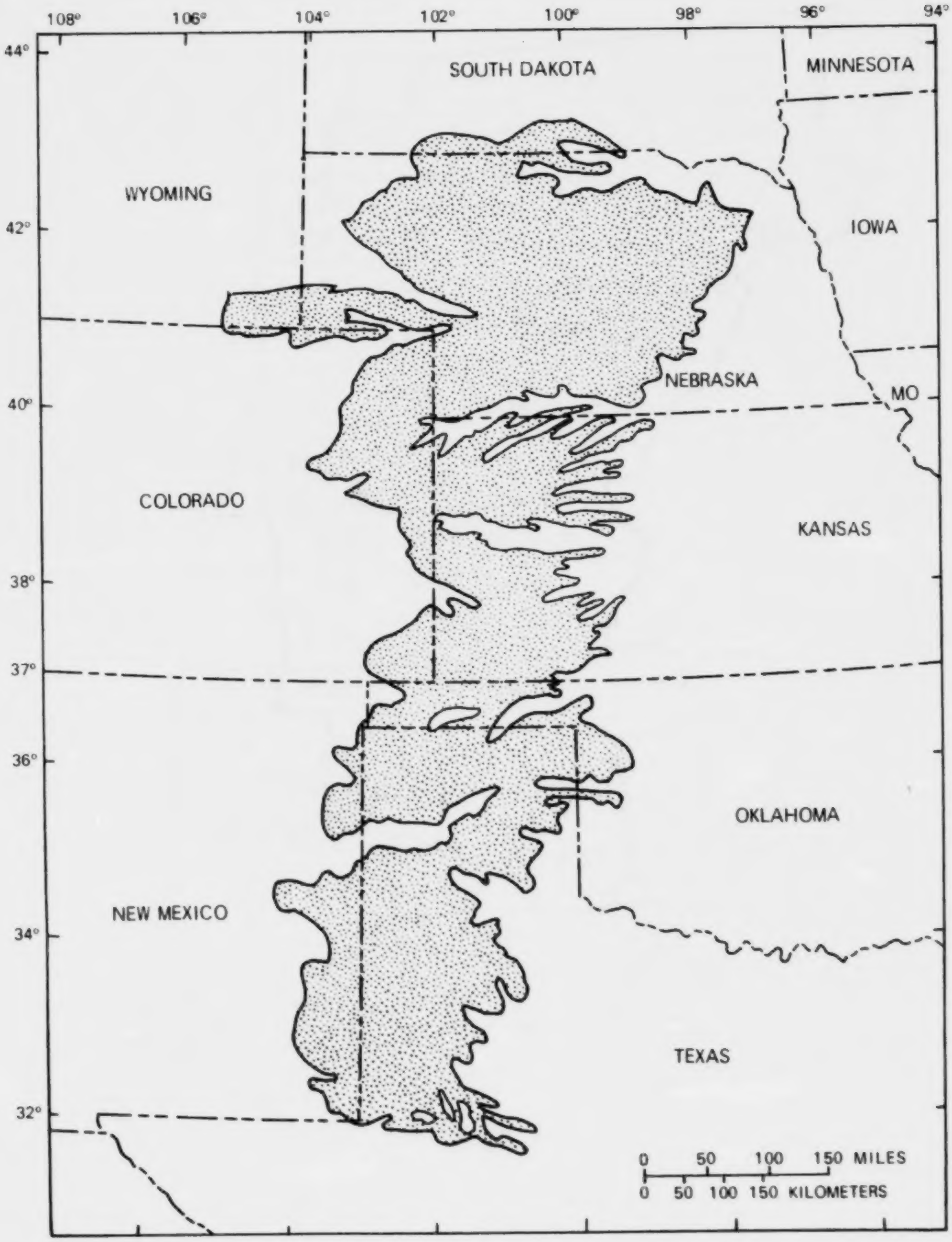
Precipitation and Evapotranspiration

Figure 5 shows the average annual precipitation, based on state climatic divisions, across a region which closely approximates the Irrigated Great Plains. The range is from 74 centimeters (cm) in southeastern Nebraska to 33 cm in northern Montana and southeastern New Mexico to 26 cm in Wyoming's Bighorn Basin. A distinct east-to-west decrease in annual precipitation is apparent, along with a south-to-north decrease in the eastern half of the region. Along the region's western boundary, there is less change in precipitation from south to north and it follows no discernible pattern. Agriculturalists and others have long cited 51 cm as being the average annual precipitation needed for a stable economy based on dryland crop production (Powell, 1878; Webb, 1931). Of the 53 climatic divisions included in Figure 5, 39 receive an average yearly precipitation at or below this amount.

Seasonality--

Distribution of average annual precipitation, by season, for select climatic divisions is shown in Figure 6. This information adds an important dimension to the rainfall picture and partially explains why dryland agriculture (though precarious) is possible in this region. Rainfall in the Plains displays a marked seasonality, with most of the moisture arriving in the spring and summer. Except in the western portion of the region, the percentage which is received during the growing season (May to September) 1/

1/ The actual length of growing season in the Irrigated Great Plains decreases from south to north. The period May to September is used as an average.


108°
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98°
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42°
40°
38°
37°
36°
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32°
SOUTH DAKOTA
MINNESOTA
WYOMING
IOWA
NEBRASKA
MO
COLORADO
KANSAS
OKLAHOMA
NEW MEXICO
TEXAS
0 50 100 150 MILES
0 50 100 150 KILOMETERS

Figure 4. Location of the Ogallala formation, a multi-state geologic unit and an important aquifer.
(Weeks, 1978)

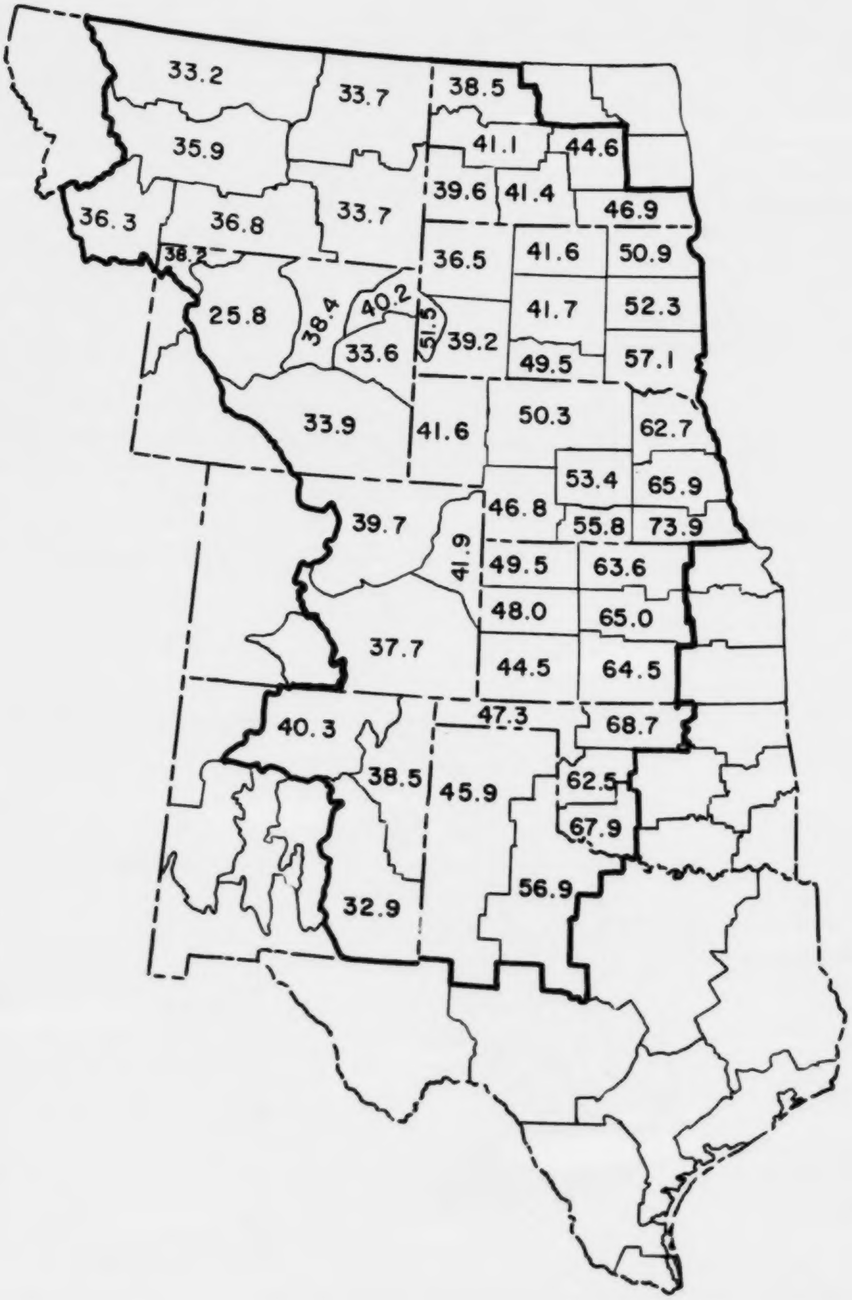
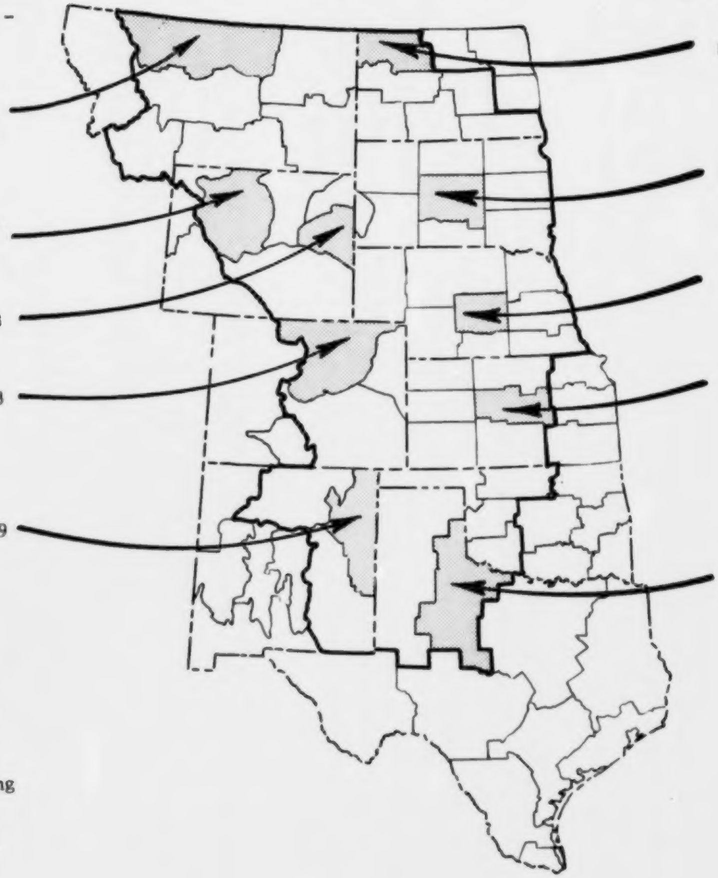

33.2
33.7
38.5
35.9
41.1
44.6
36.3
36.8
33.7
39.6
41.4
46.9
38.2
36.5
41.6
50.9
25.8
38.4
40.2
51.5
41.7
52.3
33.6
39.2
49.5
57.1
33.9
41.6
50.3
62.7
53.4
65.9
46.8
39.7
55.8
73.9
41.9
49.5
63.6
48.0
65.0
37.7
44.5
64.5
47.3
40.3
68.7
38.5
45.9
62.5
67.9
56.9
32.9

Figure 5. Average annual precipitation (cm) in a region composed of climatic divisions within the ten Great Plains states. Boundaries are similar to those of the Irrigated Great Plains. (Modified from: U.S. Dept. of Commerce, Climatic Atlas of the United States, 1968.)

Seasonal Precip./Ave. Annual Precip.

Winter	Spring	Summer	Fall	Growing Season
- - - - -	p e r c e n t	- - - - - -		
10	27	45	18	69
10	37	31	22	57
9	36	38	17	63
11	32	40	17	63
11	20	41	28	69



Seasonal Precip./Ave. Annual Precip.

Winter	Spring	Summer	Fall	Growing Season
- - - - -	p e r c e n t	- - - - - -		
8	24	51	17	72
8	32	43	17	66
8	31	43	18	69
10	30	39	21	65
14	32	29	25	58

Definitions:

Winter - Dec, Jan, Feb
Spring - Mar, Apr, May
Summer - June, July, Aug
Fall - Sept, Oct, Nov
Growing Season - May to Sept[1/]

[1/] The actual length of growing season in the Irrigated Great Plains decreases from south to north. The period May to Sept is used as an average.

Figure 6. Distribution, by season, of average annual precipitation in select climatic divisions in the Irrigated Great Plains.

increases from south to north. This occurrence, along with a south-to-north decrease in evaporation, permits more crop production in the drier northern plains than would otherwise be the case.

Despite the rainfall received during the growing season, supplemental water is desirable (and in many places, necessary) in most years to assure a good crop. Thus, rainfall seasonality affects irrigation needs and practices throughout the Irrigated Great Plains.

Variability--

Another characteristic of precipitation in this region is its variability. Generally speaking, the lower the average annual precipitation in an area, the greater the variability--that is, greater variation in the amount of precipitation received from year to year. In the Irrigated Great Plains, the expected deviation from mean annual precipitation ranges from 15 percent to 25 percent (Biel in Strahler, 1969). In other words, if the mean annual precipitation is 40 cm and the expected deviation is 25 percent, then 30 cm might fall in one year and 50 cm the next year.

Not only does precipitation in the region vary a good deal from year to year but also from place to place within any given year. Consider, for example, the 1929 and 1930 precipitation records for Mitchell and Scottsbluff, Nebraska--towns only eight miles apart (Table 3). In 1929 and 1930, Mitchell received a two-year total of 88.6 cm and Scottsbluff received a similar two-year total of 88.7 cm of precipitation. Yet, for each of the individual January-to-December periods, Mitchell's annual precipitation was significantly different from that of Scottsbluff; 9.5 cm lower in 1929 and 9.4 cm higher in 1930.

Corn, an important crop in the Irrigated Great Plains, has acute water needs during particular periods of its growth cycle. When grown in the area around Mitchell and Scottsbluff, Nebraska, for example, the period of late July and much of August is crucial. In August, 1929, Mitchell received 1.3 cm of rainfall. During the same month in the following year, it received 10.5 times that amount, or 14.4 cm.

Such yearly and monthly variability in precipitation has a significant impact on Great Plains agriculture. It means that many farmers are generally going to need a supplemental supply of water in order to maintain an economically-viable level of crop production over an extended period of years.

Intensity--

Rainfall intensity is a third factor which must be mentioned in a discussion of agriculture and its relationship to water quality in the Irrigated Great Plains. Figure 7 is a rainfall intensity map which shows the maximum 30-minute rainfall which could be expected during any two-year period. The 6 cm isopluvial line, for example, connects points where 6 cm of rain could be expected to fall within a 30-minute period (considered a quite intense rainfall) during any two consecutive years. The 6 cm

TABLE 3. MONTHLY AND ANNUAL RAINFALL (IN CM), MITCHELL AND SCOTTSBLUFF, NEBRASKA FOR 1929 AND 1930 [1]

	Total	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						- - - - - -	Growing	season	- - - - - -				
1929: Mitchell	35.32	0.18	0.48	2.08	6.2	4.16	7.72	1.88	1.37	7.82	2.64	0.79	0.00
1930: Mitchell	53.23	0.40	0.99	0.28	7.0	9.83	3.88	0.66	14.48	8.76	5.92	0.76	0.20
1929 + 1930	88.55												
1929: Scottsbluff	44.88	0.46	1.3	4.3	7.92	3.05	6.6	4.55	1.95	8.25	4.14	2.34	T [2]
1930: Scottsbluff	43.81	1.7	0.56	0.56	4.4	10.26	3.25	1.19	10.0	4.6	4.8	2.06	0.43
1929 + 1930	88.69												
Mitchell: 30-year ave. (1941-70)	35.54												
Scottsbluff: 30-year ave. (1941-70)	37.01												

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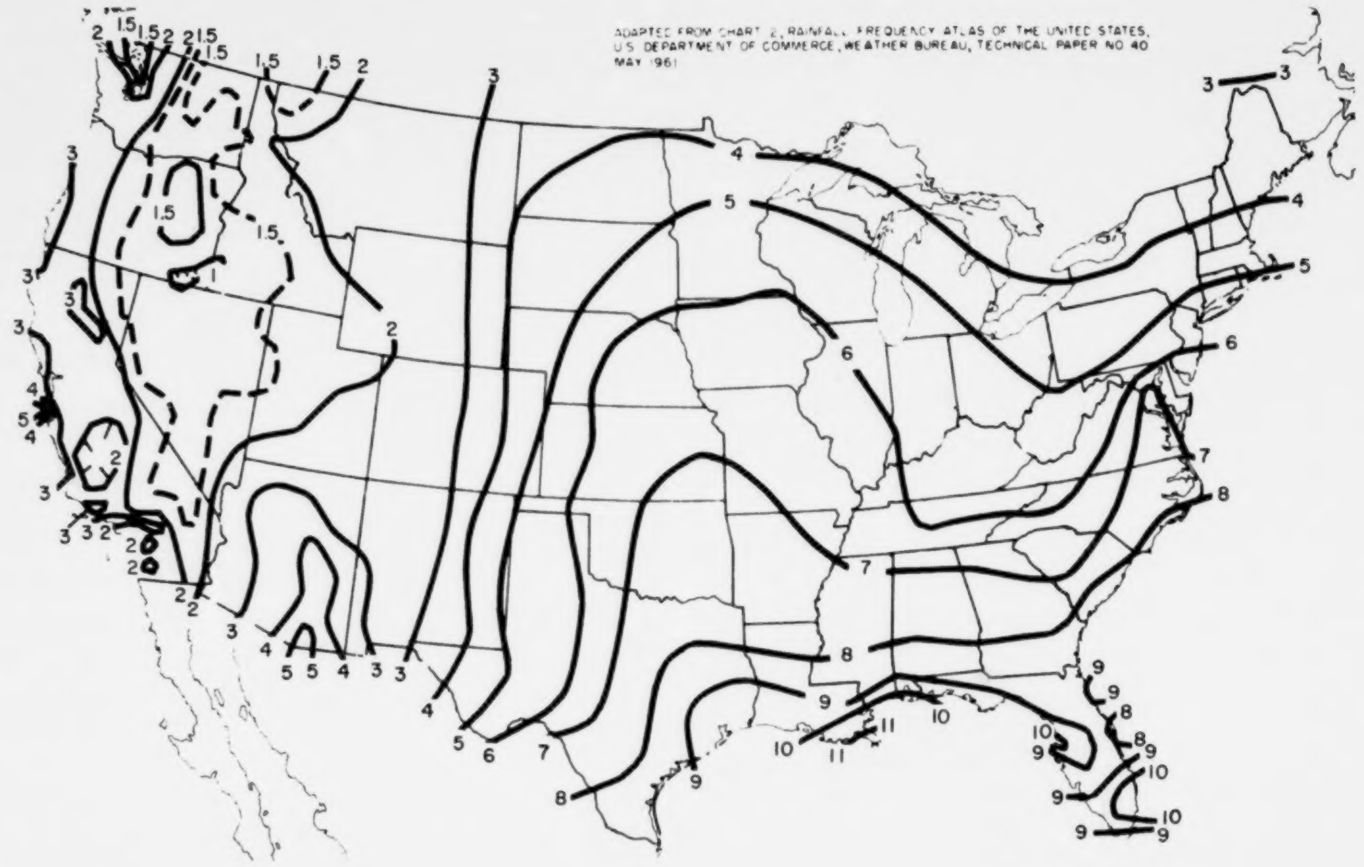
[1] From Thornthwaite (1936)

[2] Trace = less than 0.025 cm



ADAPTED FROM CHART 2, RAINFALL FREQUENCY ATLAS OF THE UNITED STATES, U.S. DEPARTMENT OF COMMERCE, WEATHER BUREAU, TECHNICAL PAPER NO 40 MAY 1961

Figure 7. For the United States, maximum 30-minute rainfall intensities in centimeters (cm) which can be expected during any two-year period. (Isopluvial interval = 1 cm). (Modified from: Hershfield, 1961)

isopluvial line arches northward over the Great Plains, reflecting the influence of the Gulf of Mexico as a moisture source. Thus, intense rainfall is a characteristic common to much of the Irrigated Great Plains, but particularly in the southern portion of the region.

When such large quantities of water fall on the ground during short periods of time, potential pollutants such as fertilizers, pesticides, and sediments can be washed from cultivated fields and into receiving waters. Fields planted to row crops are more vulnerable in this regard than are those with cover crops, especially on the steeper slopes. If the heavy rains occur early in the growing season, when the plants are still small and much of the ground is exposed, the impact is likely to be even greater.

Most of the Irrigated Great Plains has recorded its maximum 24-hour rainfall (that is, the largest amount of rain to fall in a 24-hour period) during the summer months (Weather Bureau, 1963). The importance of this precipitation occurrence lies in the fact that the summer season is when the impact on agriculturally-related water quality problems is apt to be the greatest. In fact, in parts of the region, prolonged heavy rains have a greater impact than do applications of irrigation water because the farmer has no control over rainfall timing and amount (D. Watts, per. com.).

Evapotranspiration--

Transpiration is the process by which plants transpire and release water to the atmosphere. When combined with the evaporation of water from the soil surface, the collective term of evapotranspiration (ET) is used. Evapotranspiration can be thought of as an 'invisible river' which carries water away from an area just as assuredly as a regular river. Average evapotranspiration rates for the Great Plains during the summer may range from 0.4 cm a day in the northern plains to 0.6 cm a day in the southern plains (J. Stone, per. com.). Perhaps more important, however, are the deviations from average. Corn, for example, can experience a peak ET rate of 0.8 to 0.9 cm a day in the northern plains and 1.1 to 1.2 cm a day in the southern plains (D. Watts, per. com.).

Evapotranspiration continually transports water from the soil through the plant to the atmosphere, and in the process, performs such vital functions as supplying nutrients to the plant and regulating its temperature. Over the course of a growing season, large quantities of water are required to accomplish these ends. As a case in point, total ET for corn during the growing season may vary from approximately 56 cm in the northern plains to as much as 80 cm in the southern plains. Expressed another way, one corn plant in the Great Plains can evapotranspire from 87 to 125 liters of water during the growing season (D. Watts, per. com.).

Theoretically, it is when evapotranspiration exceeds rainfall that irrigation is needed. The larger the difference between these two parameters, the more irrigation water will be required. This is one of the reasons, then, that evapotranspiration must be considered when discussing management alterantives to help reduce nonpoint source pollution from irrigated agriculture. In addition, as water evapotranspires into the atmosphere, it leaves behind the salts which it contained. On occasion, this salt residue can contribute to an irrigation-related water quality problem.

In summary: rainfall seasonality, variability, and intensity, along with evapotranspiration have had, and will continue to have, an influence on agriculture, on irrigation, and on water quality in the Great Plains.

Irrigated Crops and Water Sources

Crops--

The United States has about 24.5 million hectares of farmland under irrigation (*Irrigation Journal*, 1978). Of this amount, the Irrigated Great Plains accounts for about 9 million or 37 percent (see Tables 4 and 5). Data on the region's five major irrigated crops--corn, alfalfa, sorghum, soybeans, and cotton--make possible further evaluation and comparison.[1/] The distribution of these crops within the Irrigated Great Plains is shown in Figures 8 through 12. This distribution is based simply on the number of irrigated hectares of each crop in the various subareas.

Figure 12, for example, shows that irrigated cotton is grown mostly in eastern New Mexico, northern Texas, and southwestern Oklahoma. On the other hand, alfalfa is spread across all ten states, as shown in Figure 9. Such information is useful when considering potential nonpoint source pollution from irrigated agriculture in the entire Irrigated Great Plains. First, it shows in broad perspective where row crops are located, as opposed to cover crops. Second, it suggests where crop-specific farm practices would most likely be found. Third, it makes clear that for a widely-dispersed crop like corn, the range of irrigation management practices is going to be greater than for a crop with a more limited geographic distribution such as cotton. This is because the widely-dispersed crop will encounter a greater variety of physical conditions such as different lengths of growing season, soils, topography, and precipitation.

The concentration of a particular crop within a *portion* of a subarea does not appear on these maps. Rather, such irrigated hectares would be included in the overall figure for the entire subarea in which that crop concentration is located. The maps should be examined with this fact in mind.

[1/] While the amount of cropland planted to irrigated soybeans is not large in comparison to the other four crops, it is expected to increase in the future.

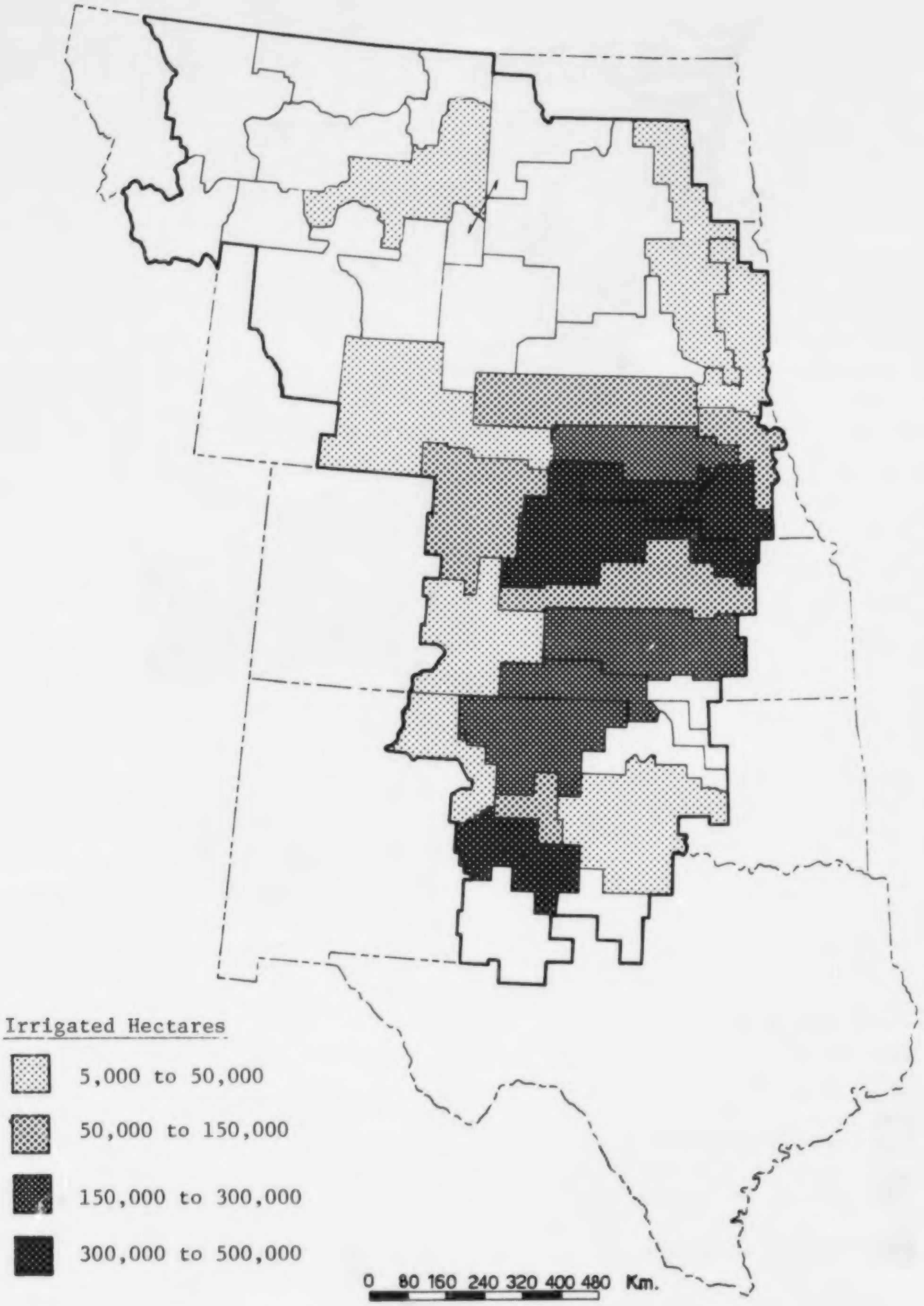

Irrigated Hectares
5,000 to 50,000
50,000 to 150,000
150,000 to 300,000
300,000 to 500,000
0 80 160 240 320 400 480 Km.

Figure 8. Distribution of irrigated corn in the Irrigated Great Plains, based upon irrigated hectares of corn (5,000 or more) in the various subareas.

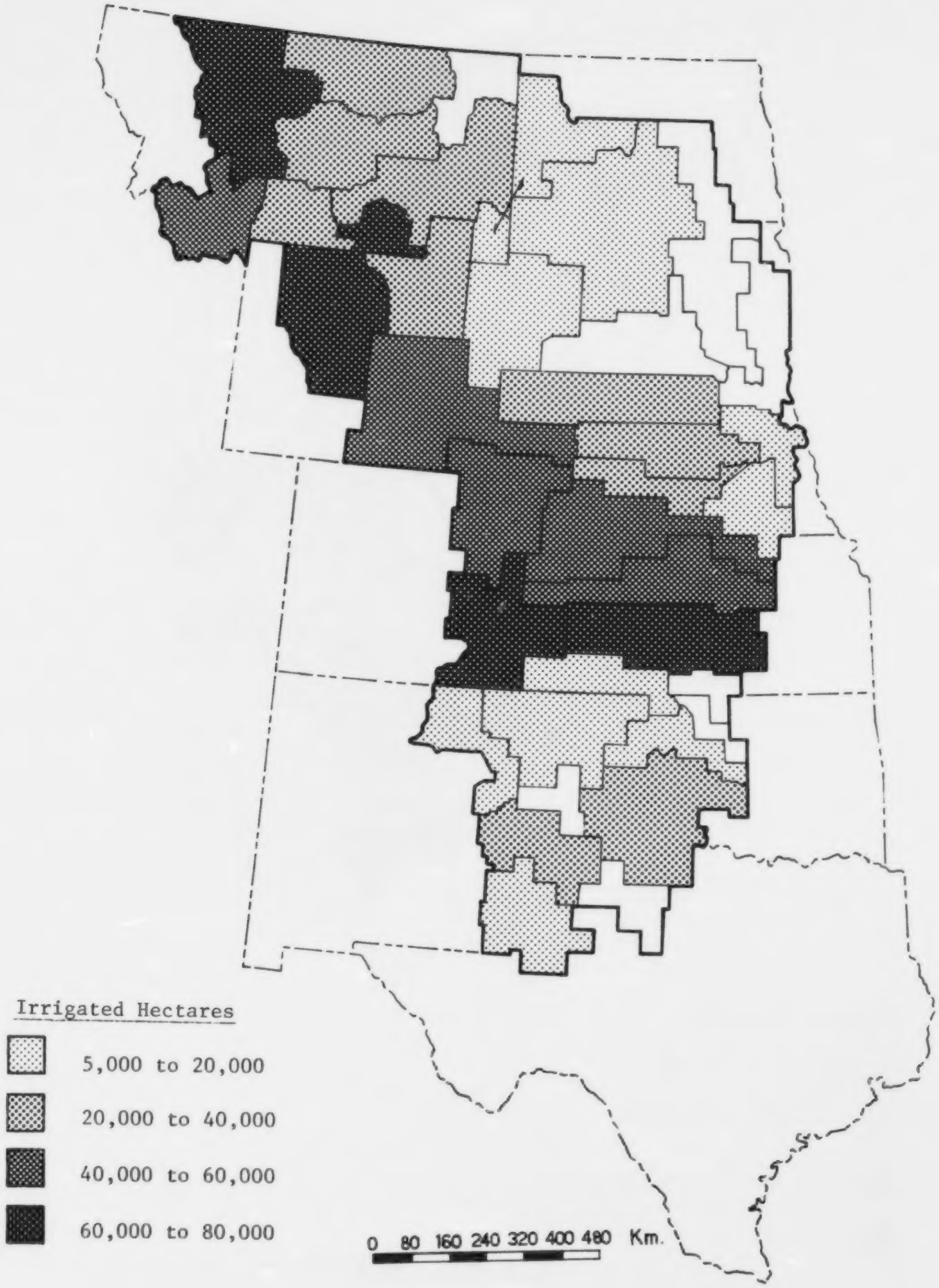

Irrigated Hectares
5,000 to 20,000
20,000 to 40,000
40,000 to 60,000
60,000 to 80,000
0 80 160 240 320 400 480 Km.

Figure 9. Distribution of irrigated alfalfa in the Irrigated Great Plains, based upon irrigated hectares of alfalfa (5,000 or more) in the various subareas.

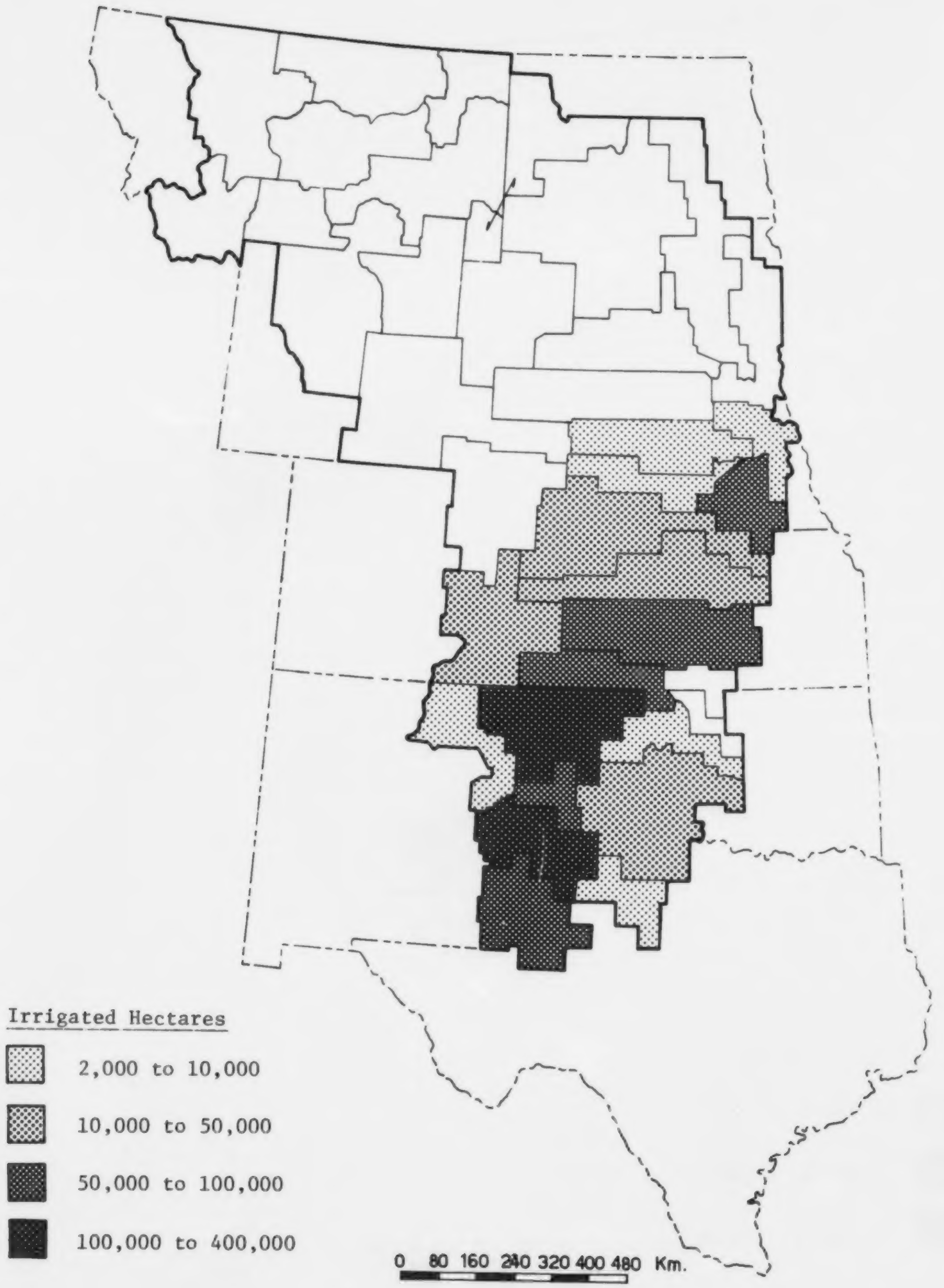

Irrigated Hectares
2,000 to 10,000
10,000 to 50,000
50,000 to 100,000
100,000 to 400,000
0 80 160 240 320 400 480 Km.

Figure 10. Distribution of irrigated sorghum in the Irrigated Great Plains, based upon irrigated hectares of sorghum (2,000 or more) in the various subareas.

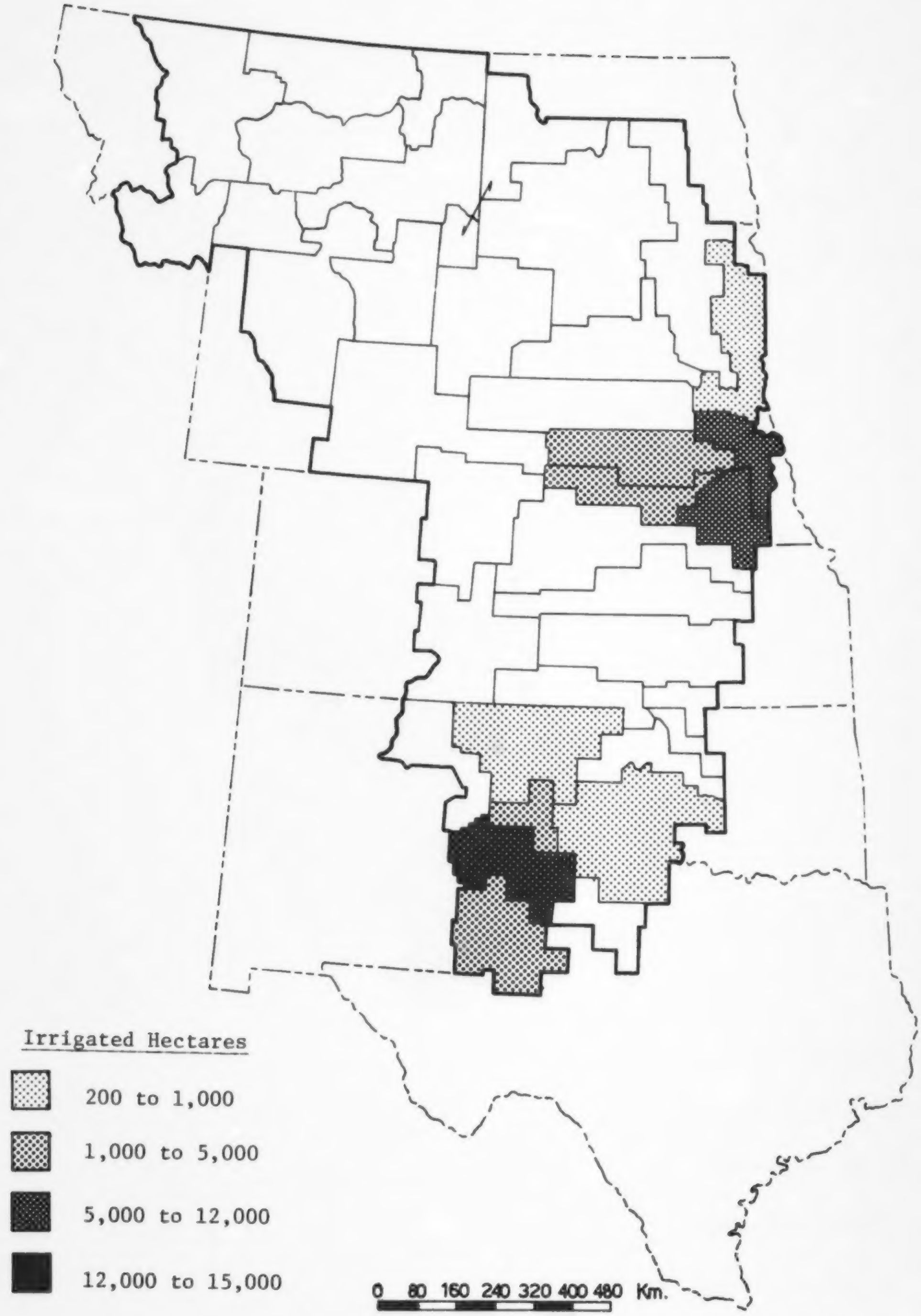

Irrigated Hectares
200 to 1,000
1,000 to 5,000
5,000 to 12,000
12,000 to 15,000
0 80 160 240 320 400 480 Km.

Figure 11. Distribution of irrigated soybeans in the Irrigated Great Plains, based upon irrigated hectares of soybeans (200 or more) in the various subareas.

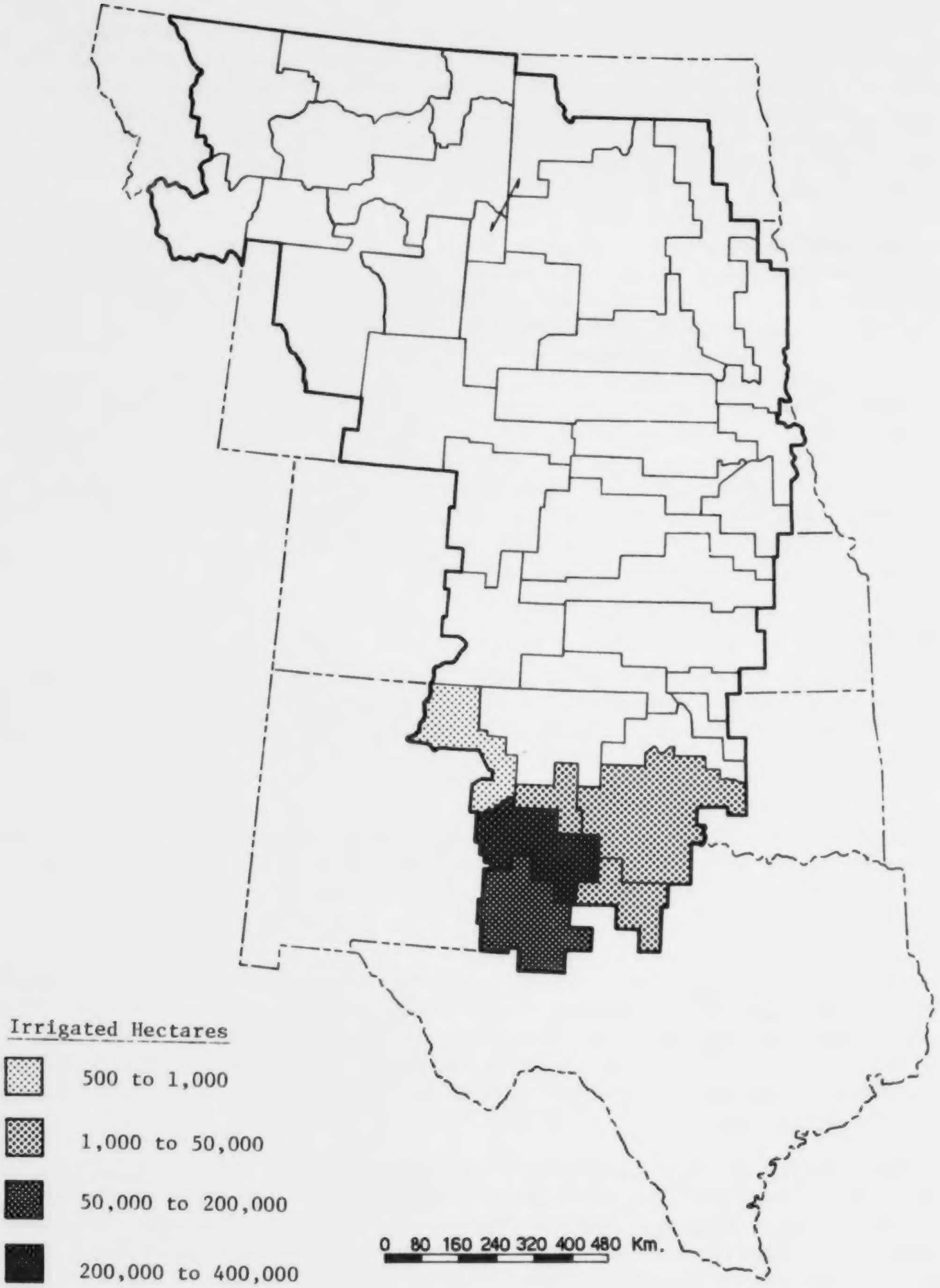

Irrigated Hectares
500 to 1,000
1,000 to 50,000
50,000 to 200,000
200,000 to 400,000
0 80 160 240 320 400 480 Km.

Figure 12. Distribution of irrigated cotton in the Irrigated Great Plains, based upon irrigated hectares of cotton (500 or more) in the various subareas.

Further crop information is displayed in Table 4. In this table the estimated number of irrigated hectares for each of the five crops in all the subareas is listed as a percentage of the total irrigated hectares. For example, Subarea 1010 (the Lower Yellowstone drainage) has 21 percent of its 87,000 irrigated hectares in corn, while in Subarea 1109 (part of the Canadian River drainage), 26 percent of 793,000 irrigated hectares are planted to corn.

The most intensively irrigated subarea--Subarea 1205--shows the most diversification among these five crops. Of its total irrigated hectares, 25 percent is in corn, 25 percent is in sorghum, and 29 percent is in cotton. In contrast, Subarea 1021 which is also intensively irrigated, has 71 percent of its total irrigated hectares in corn. Thus, within Subarea 1205 (Brazos headwaters) one might expect a variety of management practices reflecting the needs of the different crops (and also the longer growing season). On the other hand, in Subarea 1021 (Platte River drainage) the management practices would be those commonly associated with the cultivation of irrigated corn (and a shorter growing season). Such information should be considered when alternatives for managing nonpoint source pollution from irrigated agriculture are being examined, particularly in a region as large and diverse as the Irrigated Great Plains.

Water Sources--

Available figures show that for all ten Great Plains states combined, the ratio between the number of hectares irrigated with groundwater and the number of hectares irrigated with surface water is approximately 4 to 1. A state-by-state listing is presented in Table 5. Groundwater is indeed the major water source for irrigation in the region.

Table 5 also shows estimates for the number of hectares under the two major methods of irrigation--surface and sprinkler. These figures required extensive interpretation and thus are estimates which should be used with care.

Groundwater studies--Concerns have arisen over the effects of continued intensive groundwater irrigation on the resources and economy of the Great Plains. Serious questions are being asked, such as: How long will the groundwater last? What will happen when it is no longer economical to pump groundwater? How will irrigated agriculture fare in the face of increased urban and energy uses of water in the Great Plains?

Three major studies extending over several years have recently begun to address these and other questions. The U.S. Geological Survey's five-year "High-Plains Regional Aquifer-System Analysis" is the most extensive of these investigations. Another is a three and one-half year study of the impact on the nation's agribusiness of declining groundwater supplies in the High Plains. This work is being done under the auspices of the U.S. Department of Commerce's Economic Development Administration which, in turn, has contracted the services of a private consulting firm, Camp Dresser and McKee, Inc., of Austin, Texas. The U.S. Bureau of

TABLE 4. IRRIGATED LANDS PLANTED TO THE FIVE MAJOR CROPS AS A PERCENT OF THE TOTAL IRRIGATED HECTARES IN EACH SUBAREA

Subarea	Total irrig. hectares (1,000)	Corn	Alfalfa	Sorghum	Soybeans	Cotton
		- - - - - - - - - -	- - - -	percent	- - - - - - - - - - -	
1002	136		38			
1003	144	0.6	42			
1004	40	3	56			
1005	54	7	42			
1006	10	10	39			
1007	65	3	40			
1008	220	2	28			
1009	60	0.2	37			
1010	87	21	28			
1011	24	10	41			
1012	44	2	21	0.2		
1013	20	5	30	2		
1014	9	22	22	8		
1015	213	60	11	0.2		
1016	17	59	24	3		
1017	34	82	11	2	3	
1018	482	8	12			
1019	385	28	15			
1020	285	72	8	1	1	
1021	567	71	5	1	0.7	

(Continued)

TABLE 4. (Continued)

Subarea	Total irrig. hectares (1,000)	Corn	Alfalfa	Sorghum	Soybeans	Cotton
		- - - - - - - - - - -		percent	- - - - - - - - - - -	
1022	193	72	4	1	5	
1025	628	64	8	2		
1026	118	45	38	12		
1027	586	81	2	9	1	
1102	160	10	42	11		
1103	521	40	14	14		
1104	405	38	4	18		
1105	15	3	20	4		
1106	4	2	45	3		
1108	44	25	17	5		2
1109	793	26	2	32		
1110	43	6	44	20		0.3
1112	313	23	1	32	1	6
1113	220	4	14	16		21
1205	1,292	25	2	25	1	29
1206	21		5	32		46
1208	393		5	23		50
Total	8,645					

Note: Figures for irrigated hectares of corn, alfalfa, sorghum, soybeans, and cotton--upon which the above crop percentages are based--were secured from the sources discussed on pages 5 and 6 of this manual.

TABLE 5. IRRIGATED HECTARES BY SOURCE OF WATER AND IRRIGATION METHOD IN THE IRRIGATED GREAT PLAINS [1]

	Total irrigated hectares	Groundwater			Surface Water		
			Irrigation method			Irrigation method	
		Total	Sprinkler	Surface	Total	Sprinkler	Surface
	(1,000)	- - - - (1,000 hectares)- - - -			- - - (1,000 hectares) - - -		
Colorado	753 [2]	300	158	142	311	17	294
Kansas	1,384	1,330	415	915	54	25	29
Montana	558	41	34	7	517	89	428
Nebraska	2,902	2,367	1,032	1,335	535	78	457
New Mexico	240	221	134	87	19	10	9
North Dakota	56	36	34	2	20	5	15
Oklahoma	385	337	191	146	48	7	41
South Dakota	151 [2]	75	60	15	71	61	10
Texas	2,681	2,681	654	2,027	--	--	--
Wyoming	263	30	17	13	233	9	224
Total	9,373	7,418	2,729	4,689	1,808	301	1,507

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[1] Table prepared by M. Twersky. The information was compiled from and cross-checked with Irrigation Journal's 1977 Irrigation Survey, the latest available state Agricultural Statistics, and irrigation extension experts in the various states.

[2] These two states have a small number of hectares where both surface and groundwater are used. The numbers are not included in this table.

Reclamation is conducting the third investigation--a four-year effort which will focus on the High Plains south of the Arkansas River.

As a result of these and perhaps other studies, it is possible that recommendations may eventually be made which, if implemented, could affect agriculturally-related water quality programs in the Great Plains. For this reason, planners and others, who are developing management alternatives for lessening the negative effects of irrigated agriculture on the quality of water, might find it useful to follow the progress of these investigations.

SECTION 2

WATER QUALITY OF IRRIGATION RETURN FLOWS IN THE GREAT PLAINS

by
J. R. Gilley, D. G. Watts, F. W. Roeth, and M. Twersky

Irrigation is an important tool in the stabilization of crop production and farm income in the Great Plains. It provides the means to overcome the adverse effects of highly variable and often inadequate precipitation. Irrigated crop production requires many of the same management practices as dryland agriculture. However, some practices, particularly the application of nutrients and pesticides, are likely to be more intensive in areas where crops are irrigated. While this generally leads to increased crop yields, it also increases the possibility in some situations for negative impacts on the environment. For example, excessive amounts or mismanagement of water, nutrients, or pesticides or the use of improperly designed or managed irrigation systems can create nonpoint source pollution problems.

One of the major problems facing modern agriculture is that of developing management practices for the maintenance of high production levels while minimizing hazards to the environment. Such practices must be tailored to fit the varying conditions imposed by soil, climate and crop. An optimum set of practices at one location may be disastrous at another where conditions are entirely different. Appropriate management practices for a given set of conditions can be much better defined and implemented when both the people who manage agricultural production and those responsible for environmental protection have a clearer understanding of the general interrelationships that exist between soil, plant, water and management practices. A grasp of a few basic concepts is extremely helpful in understanding how current irrigation practices affect the quality of surface runoff and subsurface drainage water from irrigated lands. Improved understanding enhances our ability to alter these practices in order to improve the environment and maintain an economic level of production.

This chapter presents some important agronomic concepts and practices related to irrigation management. Soil-water-plant relationships, surface and subsurface return flows, nutrients and pesticides, irrigation methods and systems, and related management practices are considered as parts of the entire agricultural production system. These parts are all interrelated such that modifications of one may change the other with subsequent effects on the extent and magnitude of the irrigation water quality problem.

DEFINITION AND DESCRIPTION OF IRRIGATION RETURN FLOWS

Irrigation return flow (IRF) is that part of the water supply (precipitation plus irrigation) which is not used to supply the crop evapotranspiration demand or the necessary leaching requirement and which eventually travels back to surface or groundwater sources. The two broad categories of irrigation return flow are surface water runoff and deep percolation. The quantity and quality of IRF are influenced by many natural phenomena as well as man-controlled management practices (Figure 13). The management of the irrigated agricultural production system affects both the amount and quality of the water that flows back to surface or groundwater sources. In this manual, the discussion of return flow is limited to flow from irrigated lands. Over 200 references describe the complex nature of IRF (Walker, 1977).

Soil-Plant-Water Concepts

The important factors affecting the balance of water and agrochemicals in an irrigated agricultural production system are shown in Figure 14. The water balance shown in Figure 14 can be summarized as follows:

$$\left\{\begin{matrix}\text{Precipitation}\\ + \\ \text{Irrigation}\end{matrix}\right\} - \left\{\begin{matrix}\text{Transpiration}\\ + \\ \text{Evaporation}\\ + \\ \text{Increase in}\\ \text{Stored Soil}\\ \text{Water}\end{matrix}\right\} = \left\{\begin{matrix}\text{Surface Water}\\ \text{Runoff}\\ + \\ \text{Deep}\\ \text{Percolation}\end{matrix}\right\} = \begin{matrix}\text{Irrigation Water}\\ \text{Return Flow}\end{matrix}$$

Water starts infiltrating into the soil as soon as irrigation water is applied. The rate of water infiltration decreases from relatively high rates during the early phase of an application to a nearly constant rate. When the rate of water application exceeds the soil infiltration rate, water starts collecting on the soil surface. The time at which this happens depends on the type of soil, irrigation system, and water delivery rate. Most of the accumulated surface water eventually becomes surface water runoff, although some of the water will stay on the soil surface in small depressions and be infiltrated after the irrigation period.

The soil acts as a reservoir holding the infiltrated water until it evaporates from the soil surface, is used by plants or percolates downward past the plant root zone. Water not retained in the root zone continues to percolate (drain) downward into the soil subsurface and acts as a solvent, transporting mineral salts, soluble fertilizers and pesticides. If this percolating water encounters relatively impermeable strata, it may form a temporary or "perched" water table and move laterally above the main groundwater level to a stream. In many cases it percolates directly to the general groundwater aquifer, becoming part of the existing groundwater supply which then may move laterally to a stream. Thus, deep percolation is part of IRF and is a carrier of soluble nutrients and pesticides.

The changes that take place in irrigation water runoff as it flows

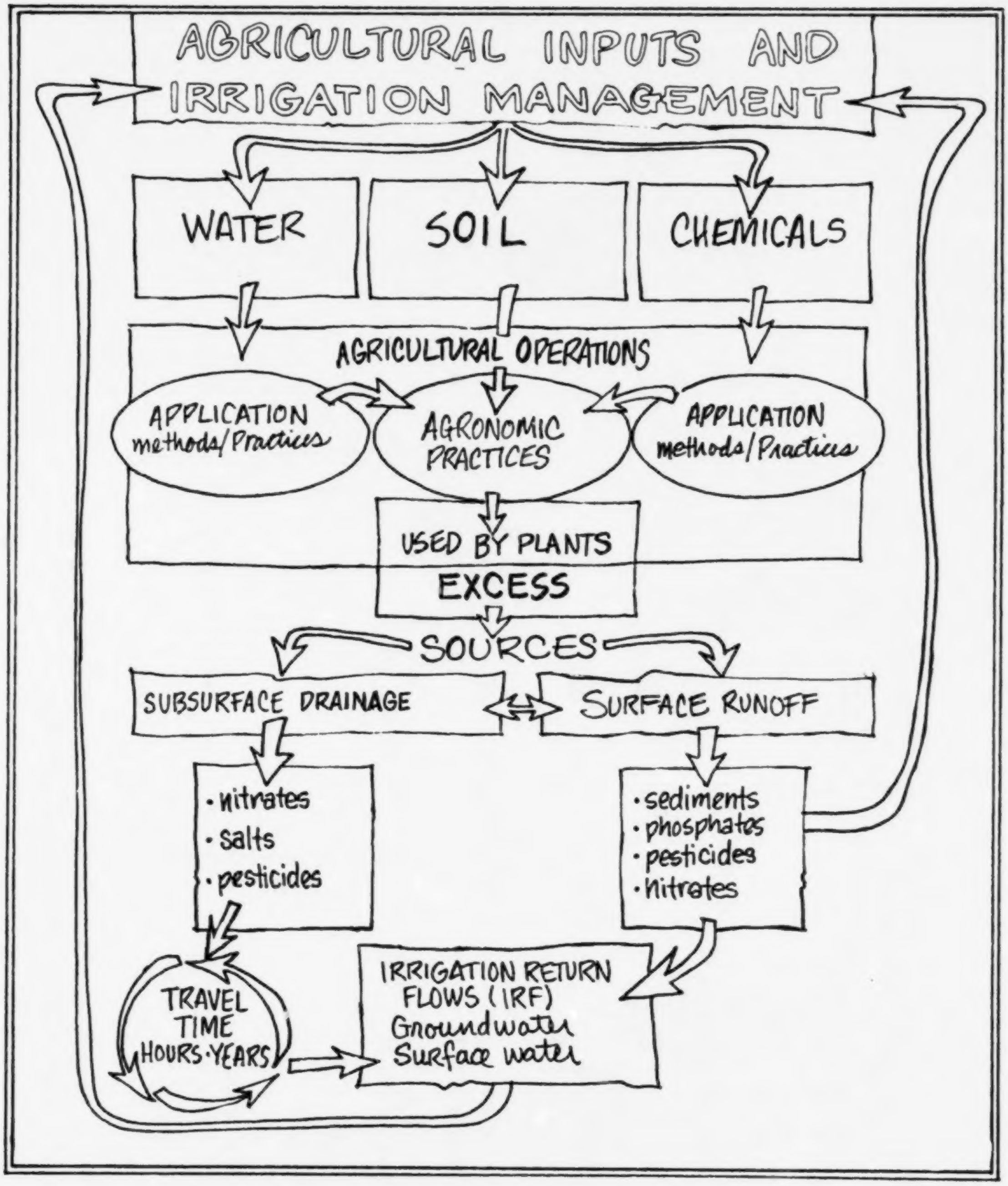
AGRICULTURAL INPUTS AND IRRIGATION MANAGEMENT
WATER
SOIL
CHEMICALS
AGRICULTURAL OPERATIONS
APPLICATION methods/Practices
AGRONOMIC PRACTICES
APPLICATION methods/Practices
USED BY PLANTS
EXCESS
SOURCES
SUBSURFACE DRAINAGE
SURFACE RUNOFF
· nitrates
· salts
· pesticides
· sediments
· phosphates
· pesticides
· nitrates
TRAVEL TIME HOURS-YEARS
IRRIGATION RETURN FLOWS (IRF)
Groundwater
Surface water

Figure 13. Return flows from irrigated agriculture.

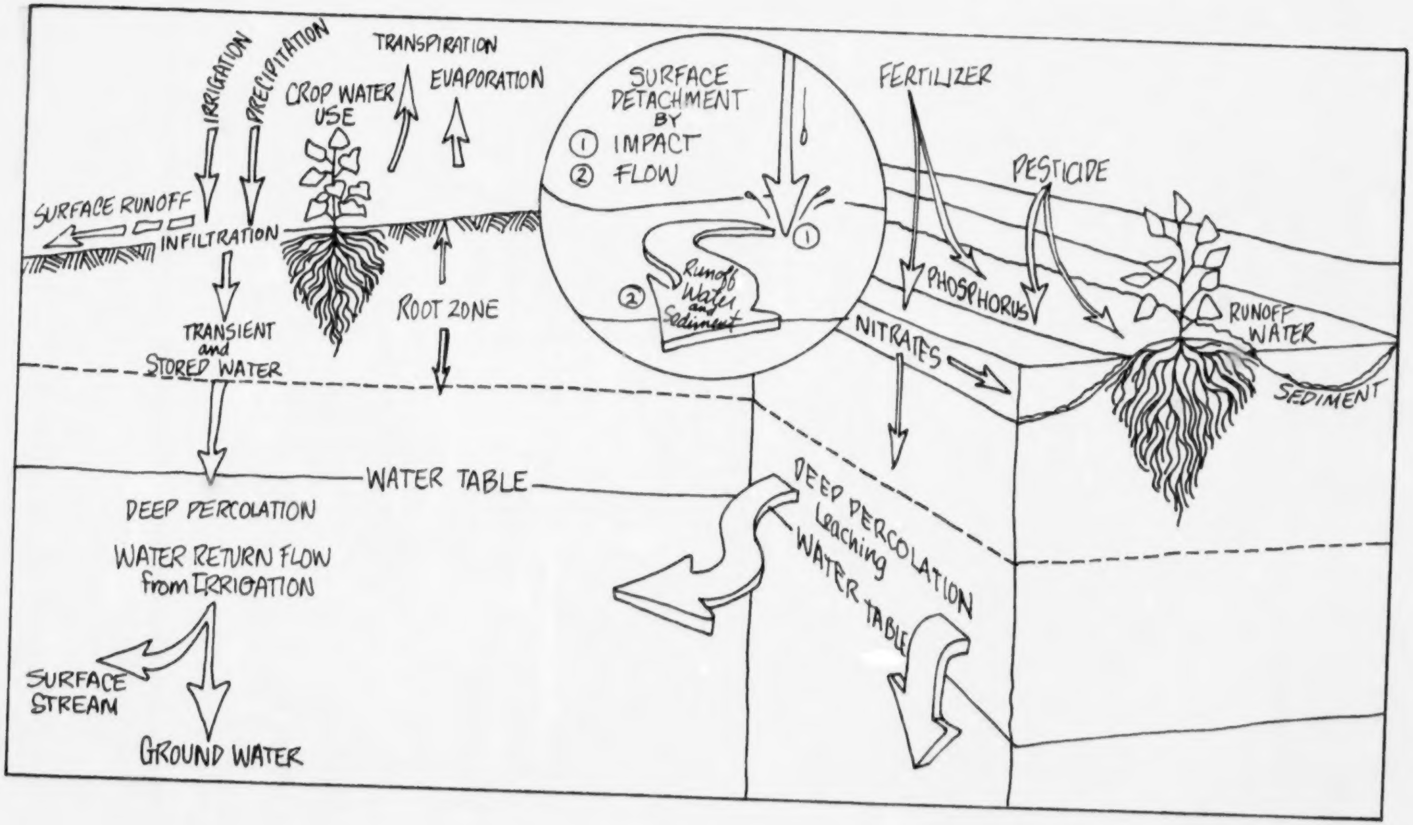
IRRIGATION
PRECIPITATION
CROP WATER USE
TRANSPIRATION
EVAPORATION
SURFACE RUNOFF
INFILTRATION
TRANSIENT and STORED WATER
ROOT ZONE
WATER TABLE
DEEP PERCOLATION
WATER RETURN FLOW from IRRIGATION
SURFACE STREAM
GROUND WATER
SURFACE DETACHMENT BY
① IMPACT
② FLOW
①
②
Runoff Water and Sediment
FERTILIZER
PESTICIDE
PHOSPHORUS
NITRATES
RUNOFF WATER
SEDIMENT
DEEP PERCOLATION
Leaching
WATER TABLE

Figure 14. Processes that influence water flow and agrochemical balances in an irrigated agricultural production system.

directly over the soil surface are quite different from those that occur when water moves as deep percolation. The quality of water flowing directly over the soil surface is affected by soil particles which are detached by both droplet impact and flowing water. Any water that travels over the soil surface to reach a stream is called surface runoff. However, the surface water runoff occurring at the lower end of an irrigation field is known as tailwater. Tailwater may evaporate, percolate, be consumed by other plants or flow into surface streams. It can also be collected and pumped back into the irrigation delivery system or used by irrigators further downstream.

Crop Water Use--

Net crop water use or evapotranspiration (ET) is a sum of the evaporation from the soil surface and the transpiration from the crop leaf surface. Early in the growing season almost all of the water use represents direct evaporation. As the crop grows, however, the proportion of ET that goes into transpiration may increase to about 90 to 95 percent for crops that fully shade the ground.

If there is adequate moisture in the soil the actual daily rate of water use by a crop depends on both the stage of growth of the crop and the potential ET, which is primarily determined by daily weather conditions. Accurate estimates of crop water use are essential for irrigation scheduling, an important water management tool. Annual, monthly, weekly and even daily crop water requirements can be determined by several methods (Jensen, et al., 1970; Jensen (ed.), 1974; and Stegman, et al., in prep.).

Normally the amount of water delivered and applied to an irrigated field must be larger than the net crop water use requirement in order to compensate for unavoidable losses to surface water runoff, deep percolation, nonuniformity of application and, in case of sprinkler systems, evaporation and wind drift losses during application. Soil, climate, crop and available water resources all influence the method used to establish the gross irrigation requirement. The complexity of these factors makes it difficult in some cases to identify the amount of water actually needed for successful irrigation. Thus, while the net seasonal water requirements of various crops are approximately known, both the actual net water use and the gross amount to be applied depend upon particular areas and situations.

Soil-Water Balance--

Although only part of the water in the root zone is used for crop growth, either excessive or deficient amounts of soil water can reduce crop production. When excess water is applied, most is lost from the root zone by deep percolation before it can be used by the growing crop. From the standpoint of production, this is not necessarily a negative impact. In some cases, deep percolation maintains a satisfactory salt balance in the root zone by removing salts which are retained in the soil as crops transpire or as water evaporates from the soil surface. Without a mechanism for salt removal, the soil would eventually become unproductive.

Effective soil-water management requires knowledge of how much water a soil can hold. The water-holding capacity of a soil is dependent on its texture, structure, organic matter content and apparent bulk density. Soil moisture and water-holding capacity may be expressed as (1) a percentage of dry weight of soil, (2) percentage of soil volume, or (3) depth of water per unit depth of soil. The latter is a convenient way of evaluating stored soil moisture and is the commonly-used means of expression.

The available soil moisture for plant use is the amount of soil moisture that can be held in the root zone between field capacity and wilting point. Field capacity is the water content of the soil after excess water has drained away and the rate of downward movement has normally ceased. (The time of drainage varies with soil texture and structure.) The permanent wilting point is the soil water content at which plants can no longer extract soil moisture at a sufficient rate to overcome moisture stress. Another term often used to describe soil moisture status is the available soil moisture deficit, the difference between field capacity and the existing soil moisture in the root zone.

Generally, the larger the percentage of fine particles in a soil, the higher the water-holding capacity. Thus, coarser-textured soils have less water available for plant use than finer-textured soils. The total soil water available for plant growth can be estimated by multiplying the available soil moisture by the rooting depth of the crop. Estimates of the available soil moisture of different soils can be found in many sources including Christensen and Westesen, 1978; Fischbach (ed.), 1977; Stegman, in prep.; Harmon and Duncan, 1978. The approximate range of available soil water for given soil textures is shown in Figure 15. As an example, the figure shows a median value of 0.16 cm of available water per cm of soil depth for a silt loam soil. Thus, in a 120 cm deep root zone, there would be .16 x 120 = 19.2 cm of water available for plant use when the soil was "full" or at the field capacity water content.

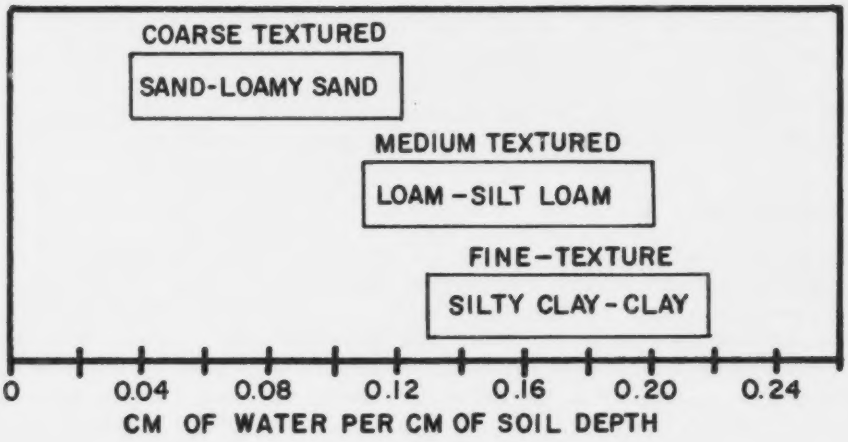

Figure 15. Representative magnitude of available water-holding capacity of agricultural soils.

IDENTIFICATION OF POLLUTANTS IN IRRIGATION RETURN FLOWS

Pollution is an undesirable change in the physical, chemical or biological characteristics of air, land and water. These changes may harmfully affect human life, animal species, industrial processes, living conditions or culture. They also may waste or cause the deterioration of raw material resources. Considerable literature exists on the evaluation of specific irrigation-related pollutants (Ayers and Westcot, 1976; Boone, 1976; Exner and Spalding, 1979; Wendt, et al., 1976). The common water quality factors in IRF and the changes in water quality likely to occur as water flows over the land surface and through the soil are summarized in Table 6.

Other factors must also be considered when determining impairments of water quality. Among them are: (a) the complexity of pollutant loading processes; (b) the large number of localized conditions affecting pollutant loading; and (c) the contribution of the same kind of pollutants from various sources, both natural and man-induced. Natural processes supply some known pollutants. The effects of these can be separated in some cases from those of man-induced processes through the use of site-specific information.

Erosion and Sediments

Soil erosion and sediment transport occur through a two-step process which involves: (a) detachment of soil particles by water droplet impact, splash, and flowing water; and (b) the transport of detached soil particles by flowing water and splash. Precipitation, irrigation and land slope are the primary sources for the energy required to accomplish this process.

In the Great Plains, most erosion is caused by precipitation, although improperly designed and operated irrigation systems can also cause erosion. The Universal Soil Loss Equation (USLE) is useful for predicting erosion from rainfall. The equation reflects how certain factors influence erosion due to rainfall. However, it has extremely limited applicability for estimating erosion caused by irrigation. These factors are discussed in great detail in other publications (Stewart, B. A., et al., 1975, 1976; Nelson, 1978; Harmon and Duncan, 1978).

Some soils are more susceptible to erosion losses than others. In general, soils that are high in silt, low in clay, and low in organic matter are the most susceptible to erosion. Thus, medium-textured soils erode more easily than the other soil types. The soil erodibility factor of the USLE is the best indicator of the degree of soil loss for various soil types.

Degree and length of land slopes also affect soil erodibility. These factors affect the transport portion of the erosion process through their influence on runoff velocity. As the slope increases, the velocity of runoff increases, and the capability of runoff to both detach and transport soil materials increases. In general, as the length of the slope is doubled, erosion losses can increase 2.5 times.

The USLE has been primarily used to predict soil erosion losses under

TABLE 6. PROBABLE CHANGES IN WATER QUALITY AS A RESULT OF IRRIGATION [1]

Quality factors	Irrigation return flow source Surface water runoff	 Deep percolation
Sediments and Colloids	Often more than in water source but may be less; highly variable.	Little or no sediment or colloidal materials in the flow.
Nitrate	More likely a slight increase than a decrease; highly variable.	Greatest hazard from heavily fertilized, over-irrigated, coarse-textured soils.
Phosphate	Content may increase, but closely correlated with erosion of fertile topsoil.	Decrease if considerable in source. Not likely to greatly increase.
Pesticides	Highly variable content. Likely associated with amount of erosion.	A reduction in many instances. Concentrations likely to be low.
Salts (Total Dissolved Solids)	Not greatly different from water sources.	Concentration increased usually 2-7 times. Depends on amount in the supply, number of times reused and the amount of residual salts being removed.
Sodium and Chloride Ions	Relatively unchanged.	Both proportions and concentration likely to increase.
Organics	Manures, debris, etc., likely to increase.	Most oxidizable and degradable materials to decrease.

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[1] Modified from Boone (1976).

limited, but defined, dryland conditons. However, factors of the equation have been applied to irrigated situations (Nelson, 1978). Soil losses expected for irrigated croplands are given in Table 7, which shows that the use of improper irrigation systems on row crops creates the greatest possible chance for soil losses. Much of the total soil loss shown in Table 7 is caused by rainfall, even under ideal management conditions.

A distinction exists between soil loss and sediment yield. Soil loss is the amount of soil set in motion without regard to distance or direction of movement. Sediment yield is that portion of the soil loss which is actually delivered to the edge of the field. The impact of sediments on water quality can be considerable and highly variable. Sediments can reduce the quality of IRF by carrying plant nutrients, pesticides and other materials adsorbed on soil particles.

Chemicals

Although nutrients and pesticides increase crop yields and improve plant quality, they can become nonpoint source pollutants. Those nutrients considered to be the greatest pollution hazards are nitrogen (N) and phosphorus (P). Primary sources of these nutrients are commercial fertilizers, animal wastes, plant residues and soils. The increased use of pesticides also has increased the potential of pesticide pollutants being carried by IRF. Much has been written about N and P and pesticide materials, their forms, characteristics, chemical make-up, and methods of transport (Frere, 1976; Stewart, B. A., et al., 1975, 1976; Int. Garrison Diversion Study Board, 1976; Harmon and Duncan, 1978).

Research indicates that under most management systems negligible quantities of soluble nitrates (NO_3) exist in surface runoff as the runoff leaves the field. A notable exception is when nitrogen is applied by injection directly into the irrigation water (fertigation). In this case, the NO_3 concentration in the runoff will be essentially the same as in the applied water. Because of this, it is essential to collect and reuse runoff or tailwater when fertigation is practiced. This will be discussed in detail in later sections.

Except for the case of fertigation, the concentrations of nitrates in surface runoff water decrease during an irrigation or rainfall event on medium- and coarser-textured soils. This occurs because nitrates readily enter the soil and are unavailable for transport in surface water runoff.

In contrast, phosphorus (P) as phosphate is usually immobile in soil because the ionic form readily adsorbs to soil particles and reacts to form insoluble salts; therefore, the amount of P moving in the soil solution is low when compared to the total amount of P in the soil. Levels of P in groundwater are not generally increased by the application of fertilizers containing P, and the movement of P in surface runoff water and deep percolation is small. Most of the P contained in surface runoff is adsorbed on the sediment.

TABLE 7. EXPECTED SOIL RESOURCE LOSSES UNDER FOUR CONSERVATION IRRIGATION MANAGEMENT OPTIONS WITH DIFFERENT CROPLAND USES [1]

Conservation management option	Cropland use [2]		
	Row crops	Broadcast crops	Forages (in rotation)
	- - - - - - - - - metric tons/ha·yr	- - - - - - - - -	
Use of most tolerable and best management practices. [3]	2.7	2.2	1.1
Use of irrigation systems and land practices which enhance soil erosion. [4]	22.4	8.3	5.6
Mismanagement of water applications with irrigation system.	8.3	5.6	2.2
Use of improper cultural or fertility practices.	6.7	5.6	1.1

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[1] Modified from Nelson, 1978.

[2] Soil resource loss based on a medium-textured soil in Nebraska with an erodibility K = 0.32, on a land slope of 3 percent, and an irrigation field run of 92 meters.

[3] Most likely soil losses under ideal management systems, primarily due to rainfall.

[4] Lack of terracing, lack of contouring, etc.

Potential losses of both N and P in surface IRF are directly related to the quantities of sediments carried in surface runoff water (Nebraska Natural Resources Commission, 1975a and 1975b; Regional Planning Office for Big Horn Basin 208 Policy Board, 1978). That is, most N and P losses in runoff result from the loss of sediments to which these elements are attached, not from N and P being directly in solution in the water. The amounts of N and P lost through erosion vary among different soils and land uses. As shown in Table 8, nutrient losses from row crops are higher than with other cropland uses because higher fertilizer applications and increased tillage (resulting in more erosion) are used with row crops.

TABLE 8. ESTIMATED AMOUNTS OF POLLUTION POTENTIAL OF SEDIMENTS AND NUTRIENTS IN SEDIMENTS IN THE NEBRASKA MIDDLE PLATTE RIVER BASIN [1]

Land use	Soil loss	Nutrients in sediments N	Nutrients in sediments P
	metric tons/ha·yr	kg/metric tons of sediments	
Row crops (corn, sorghum, soybeans)	22	46	2.1
Broadcast crops (wheat, small grains)	6	45	1.6
Forages (alfalfa, grasses)	1	16	0.3

[1] Summarized from Neb. Nat. Res. Com., Middle Platte River Basin Water Quality Management Plan, Table 6-11,12. Figures include both irrigated and nonirrigated areas.

Adsorption of pesticides to soil particles is the single most important process affecting the quantity of pesticides in IRF. While pesticide losses are low with respect to the amount of material actually applied, losses of the more soluble pesticides can reach nearly five percent of the amounts applied.

Salinity

In the arid zones of the western United States, control of salinity in the crop root zone is in many cases the primary factor determining long-term viability of irrigation agriculture. Similarly, in many parts of the northern Great Plains, salinity is a potentially serious barrier to the expansion of irrigation. This sharply contrasts with the situation in the central and southern plains where salinity presents a moderate to serious problem in only a small percentage of the soils and waters. In any area where the problem exists, however, salinity can have a very negative impact on crop production and/or on the quality of irrigation return flow. Furthermore, there is a potential for increased return flow problems in the future as lower quality water is used to develop irrigation or as percolation from new irrigation projects enters saline soil formations and flushes saline water into rivers and streams.

Salinity problems can be grouped into two broad categories of (1) natural occurrences, and (2) those resulting directly or indirectly from man's activity. The paragraphs which follow outline the causes and the general approach to the solution of some salinity problems.

Various salts (of importance to irrigation agriculture) are formed from combinations of calcium, magnesium, sodium, or potassium, with sulfate, carbonate, biocarbonate, chloride and other elements which are found in the earth's groundwater, surface streams and lakes. Salts are brought into solution as water percolates through or runs over soils and rock materials. In some cases, these sources contribute relatively high concentrations of salt into the surface water system. Water may flow through formations of very saline materials producing "mineral" springs and groundwater outflow having an extremely high salt concentration. An example of this is the series of salt flows or springs along part of the Red River and a few of its tributaries in western Texas and Oklahoma. At medium to high stream flow rates the saline spring outflow is diluted by the river water. However, when streamflow is low, the concentrated salinity from these springs drastically reduces the overall water quality in that reach of the river where they are located. Similar examples can be enumerated throughout the plains region. Saline seeps occur in agricultural zones of Montana and Wyoming; small saline stream valleys are found in the higher rainfall zone in eastern Nebraska; unuseable saline groundwater underlies many parts of the Dakotas. These are all the result of the re-entry into the water cycle of salts contained in sediments deposited millions of years ago.

When water tables are very near ground level (approximately 90 cm or less) evaporation at the soil surface can cause an upward flow of water from the water table to the top of the ground. As the water evaporates, the dissolved salts are left behind in the upper soil horizons. Over a period of time this process may cause large concentrations of salt in the soil, making it unuseable or, at best, marginal for agriculture.

Such conditions exist to a varying extent in a number of river valleys in the Great Plains. For example, parts of the Arkansas, Platte, and Republican River valleys, particularly west of the 100th Meridian, have a few areas that support only salt-tolerant vegetation. Similar areas exist in Wyoming, Montana and the Dakotas. While these saline soils may be in irrigated areas, they existed long before irrigation agriculture came on the scene. This is not to say that human activity does not contribute to the expansion (or reduction) of such saline areas. The point here is that saline soils and waters exist naturally in the Great Plains. In many parts of the plains states they may constitute a sizeable proportion of the salinity problems.

Salts in Agricultural Soils--

When irrigation water that contains various dissolved salts is applied to the land, crops remove a part or all of the water and leave the salt in the soil. If nothing is done to remove it, salinity levels will gradually increase, resulting in a continual decline in crop yield. A shift to salt tolerant crops allows continued production for a time. Eventually, however, total abandonment of production may be necessary in extreme cases.

In arid and semi-arid zones, this problem is usually resolved in two ways. First, careful attention is paid to the quality of the water applied. Irrigation waters that are high in total salts are avoided whenever possible. This reduces the amount of salt that must be contended with and delays the buildup of salinity to levels that can drastically affect production. Secondly, additional water is applied beyond the amount required to meet evapotranspiration by the crop. The extra water (leaching fraction) percolates downward through the root zone and leaches out a portion of the salts left from the water transpired by the crop. The required leaching fraction is defined as that portion of the total water application needed for leaching in order to maintain a favorable salt balance in the root zone. It may vary from only 1 or 2 percent to more than 10 or even 20 percent of the applied water, depending on the quality of the irrigation water and the salt tolerance of the crops being grown.

In many cases, particularly where surface irrigation is practiced, deep percolation due to excess water application may frequently exceed the required leaching fraction. However, in certain instances where the infiltration rate of water is very low, it may be extremely difficult to achieve the necessary leaching fraction. Examples would include very fine-textured soils having naturally low water infiltration rates, severely compacted soils (with the same result) and soils affected by excessive amounts of exchangeable sodium. Excess sodium greatly reduces the infiltration capacity and rate of movement of water through the soil. Where compaction is a problem, changes in cropping patterns and careful management may improve soil structure sufficiently to maintain an adequate leaching capability. Where sodium is a problem, reclamation through the addition of soil amendments that either contain or form calcium sulfate is almost essential. Reclamation of sodic soils is generally a several-year process.

Reclamation of saline soils is usually possible. This includes both soils that have salinized due to poor management or lack of drainage and those that have salinized under "natural" conditions. Application of large volumes of water to leach the salts from the soil is normally required. It is essential, therefore, that there be either natural or artificial drainage to remove the saline percolate or leachate that flows from the lower part of the root zone. Additionally, it should be noted that salts thus removed can be expected to emerge in the groundwater or surface water system at some other point.

Fortunately, in eastern Wyoming, in Nebraska and other Great Plains states to the south, the irrigation water is generally of good quality (low salinity levels). Furthermore, there is sufficient precipitation in at least the eastern two thirds of the region to leach accumulated salts from the crop root zone. For this reason, there are large expanses of irrigated land where no special management practices are either being used or are required to control salinity. This is particularly true in areas served by pump irrigation from high quality groundwater supplies. Where rainfall is insufficient to provide the needed leaching, excess irrigation normally solves the problem. The leachate containing the dissolved salts percolates through the root zone to the groundwater system. Over long periods of time this process results in increased salt concentration in the groundwater of such areas. However, this is normally a slow process because of the large amount of groundwater involved. Groundwater mining will probably result in the reduction of irrigation pumping from some major aquifer systems, such as the Ogallala, long before salinity concentrations become a problem. Where water is pumped from relatively shallow river valley aquifers, replenishment and dilution by recharge from the river may keep salt concentrations in the same range as that of the river water.

Problem Areas--

There are always important exceptions to general statements. For example, in western Kansas a number of salinity problems have resulted from groundwater pumping (Balsters and Anderson, 1978). Declines in groundwater levels in several areas have reduced the hydraulic head sufficiently in the freshwater aquifers to permit the inflow of very saline water from adjacent formations not tapped directly by irrigation wells. In another part of the state, recharge from the Republican River normally maintains a layer of fresh groundwater overlying the saline groundwater of the Dakota Formation. Wells located along the Republican River have intercepted a part of the river's groundwater recharge. As a result, brackish groundwater has intruded into the freshwater zone more distant from the river, greatly reducing the quality of irrigation water from wells at those locations.

The quality of surface water in the Arkansas River entering Kansas may, at times, be marginal for irrigation. Several factors contribute to this situation. First is the concentrations of salts by irrigation return flow from districts in southeast Colorado. A second important reason is that deep percolation from the irrigated lands passes through underlying saline formations. This increases the salinity of the groundwater return flow which feeds the Arkansas River. Similar examples can be cited in other states.

In other small areas of the central and southern plains and in greater parts of North and South Dakota, problems either have developed or may develop. These may be located either where individual farmers pump directly from relatively saline groundwater or where large areas are irrigated with water transported into an irrigation district from stream diversions and/or reservoir systems. In the former case, the origin of the problem is obvious; direct loading of soils with salts contained in applied waters. In the latter, the problems are more complex in origin and end result. Here, deep percolation, including the necessary leaching fraction, continually adds to groundwater storage beneath the irrigated lands. Because no large volume of groundwater is being removed by pumping, water tables are raised. Groundwater outflow to streams may increase sufficiently to bring the additional recharge into balance with the subsurface outflow system. However, the increased groundwater outflow (which constitutes a part of the irrigation return flow) will contain the more saline leachate from the crop root zone. Under some circumstances (a large groundwater reservoir, relatively small amount of percolation and/or low salinity irrigation water) the quality of the water in the groundwater system may not be much affected. In other cases, there may be a substantial decrease in groundwater quality with a corresponding increase in salinity of groundwater-fed stream flow. Furthermore, in areas that are underlain by marine deposits and/or saline waters at shallow depths (particularly in parts of the Dakotas), increased percolation from the root zone may pick up additional salts, further adding to the salt load of both the groundwater and the surface waters which are fed by that groundwater further downstream.

Requirements for Drainage--

Where additional input to groundwater percolation from irrigated lands is not balanced by additional groundwater outflow to surface streams, the water table may rise into the crop root zone. Artificial subdrainage in the form of ditches or buried drain pipes must then be installed to prevent waterlogging and rapid salinization of the upper soil profile. Here the same mechanism that leads to "natural" salinization by way of evaporation and salt deposition would come into play. The drains must maintain the water table at a depth below the surface (usually 150 cm or more) sufficient to control upper root zone salinity and also provide the outlet for both the necessary leaching fraction as well as any excess percolation.

In many cases, 20 to 40 years may elapse after project initiation before water tables rise enough so that artificial drainage may be required. An example is the W. C. Austin irrigation project in southwest Oklahoma which began full-scale operation in 1948. Currently, after 32 years of operation, subdrains are being installed on some project lands because excess percolation has finally brought the water table into the crop root zone. In some locations of the Tri-County irrigation project in south central Nebraska, the water table has risen over 100 feet during the 40-year period since development. In the next few years, additional groundwater pumping in this region may be necessary to offset continued percolation from the irrigation water applied to the project lands from stored surface supplies. Otherwise, some drain installations may be needed. Similar problems are found on the lands of the Riverton Project and Bighorn Basin Project in Wyoming where drain lines are being installed on a field-by-field basis to control the water table level and root zone salinity.

In these and similar cases, the resulting drainage waters will have increased salt content as compared to the irrigation water and will add to the salt loading of the receiving surface waters. In some instances, (the Tri-County case, for example) the increased salt concentration of the groundwater outflow is so small that it does not create any downstream problems. In others, adjustments may be necessary to deal with reduced water quality. Improved irrigation management can minimize the volume of drainage water to be dealt with and, to some extent, can reduce total salt emission from the root zone. It must be emphasized, however, that where drainage is required and is not installed, abandonment of the land for agricultural use will ultimately occur.

Conclusion--

In most of the Great Plains region, the salinity of irrigation return flow is neither a problem nor an issue. Indeed, cases can be cited where increased groundwater outflow resulting from increased percolation on project lands has created a benefit by way of increased streamflow. However, in other locations, particularly in the northern plains, concern is created by the potential problems associated with salinity in the groundwater component of irrigation return flow. A recent case in point is a large surface water impoundment project where uncertainty about the overall impact of increased salinity in downstream return flow resulted in a halt in project construction.

A favorable root zone salt balance is absolutely essential to insure the permanence of irrigation agriculture. Where supplemental irrigation is practiced with high quality water, that balance is easily achieved with little or no adverse environmental impact. At the other extreme--meeting all crop water needs with water of marginal quality--the quality of groundwater or downstream surface water is certain to be reduced by the net salt outflow from irrigated lands. The potential seriousness of salinity problems must be assessed on a case-by-case basis, based on the integrated effects of irrigation water source, water quality, rainfall amount, soil and subsoil conditions including natural salinity, groundwater systems, and crop types to be grown.

Concentration and Mass Emission

Two distinctly different but related terms are useful in evaluating and assessing water pollution from IRF. Concentration is the amount of a component or components that are dissolved or suspended in a unit volume of solution. Concentration can be expressed by weight or volume (ppm, mg/l, g/g). Mass emission is the total amount of material that is transported over some defined period of time. The mass emission term is obtained by multiplying the concentration of a material by the total volume or weight of the material in which it is dissolved or suspended. These two terms may provide different interpretations of water quality problems.

The significance of concentration or mass emission depends on the context in which the information is used. Concentration is important when defining the limits of acceptable water quality, because many systems usually respond to the degree of concentration. Mass emission is a more significant parameter when total material losses are considered. A critical limit of materials in IRF might not be reached until a certain capacity for assimilating the materials is exceeded, regardless of the concentration of materials dissolved or suspended. For example, relatively small volumes of surface runoff or deep percolation can contribute relatively low mass emissions of pollutant materials to receiving waters even if pollutant concentrations are high. However, high volumes of surface runoff and deep percolation have a considerably greater capacity for losses of pollutant materials. In this respect, mass emission is a better parameter for assessing pollution than concentration (Letey, et al., 1978).

SIGNIFICANCE OF IRRIGATION RETURN FLOWS IN THE GREAT PLAINS

The amount of water that moves as surface runoff or deep percolation must be known before the transport of sediments and chemicals from an irrigated field can be determined. Runoff return flow estimates are based on water losses from plot studies (Interagency Task Force, 1978; Boone, 1976; Irrigation Extension Personnel, per. com., 1978; Ribbens and Shaffer, 1976), and relative irrigation water application rates and efficiencies (Kruse and Heermann, 1977; Kruse, 1978). Estimates of return flows from surface runoff and deep percolation are affected by assumptions regarding the amount of water lost from either surface or sprinkler irrigation systems. The return flow factor (that portion of the gross irrigation application that is return flow) for surface irrigation systems ranges between 0.16 to 0.72, while for sprinkler irrigation systems the return flow factor ranges from 0.15 to 0.25. For a number of reasons, including amount of water supply available and irrigation methods used, this factor varies from state to state and is given in Table 9.

Some fields may have no irrigation return flow. This could occur with sprinkler systems on level land with soils having medium to fine textures (or even coarse textures if management is adequate). However, when surface irrigation methods are used, deep percolation return flows are potentially greater in coarse-textured soils because of the smaller water-holding capacities and greater hydraulic conductivities of these soils.

Extent of Irrigation Flow in the Great Plains

Irrigation return flows may be estimated by the following method:

$$IRF = A \times D \times R \qquad (1)$$

where IRF is the irrigation return flow, expressed in hectare-centimeters; A is the irrigated area, in hectares; D is the gross irrigation application,

TABLE 9. IRRIGATION RETURN FLOW IN THE GREAT PLAINS STATES BY SYSTEM TYPE AND SOURCE OF WATER [1/]

State	Gross irrigation application		Irrigation return flow factor [2/]		Irrigation return flow					Total return flow
					Groundwater		Surface water		Both sources	
	Sprinkler	Surface	Sprinkler	Surface	Sprinkler	Surface	Sprinkler	Surface	Both systems	
	- - - - cm - - - -		- - - - cm - - - -		- - - - - - - - - - - - - - - ha·cm (1,000) - - - - - - - - - - - - - -					
Colorado	51	76	0.25	0.43	2,014	4,641	217	9,608	4,641	21,121
Kansas	46	56	0.25	0.38	4,772	19,471	288	617	---	25,148
Montana	61	122	0.25	0.65	519	555	1,357	33,940	---	36,371
Nebraska	51	61	0.25	0.36	13,158	29,317	995	10,035	---	53,505
New Mexico	67	84	0.20	0.44	1,796	3,216	134	333	---	5,479
North Dakota	30	38	0.20	0.50	204	38	30	285	---	557
Oklahoma	48	58	0.20	0.21	1,833	1,778	67	499	---	4,177
South Dakota	41	51	0.20	0.25	492	191	500	128	64	1,375
Texas	46	56	0.20	0.16	6,017	18,161	---	---	---	24,179
Wyoming	53	58	0.25	0.72	225	543	119	9,354	---	10,241
AVERAGE	49.4	66.0	0.22	0.41	---	---	---	---	---	---
TOTAL	---	---	---	---	31,030	77,911	3,707	64,799	4,705	182,153

[1/] Irrigation Journal 1975-77; per. com. with state irrigation personnel.

[2/] Portion of gross irrigation requirement that becomes irrigation return flow.

in centimeters; and R is the return flow factor. On an individual farm basis, the return flow factor is a variable depending upon a host of management factors, irrigation application rates, soil properties and topography. However, for purposes of comparison, a constant factor has been used for each individual state within the Great Plains. The estimates of irrigation return flows from the individual Great Plains states are given in Table 9. Other estimates of irrigation return flows have been made for the Great Plains (Boone, 1976; Interagency Task Force, 1979).

The IRF estimates shown in Table 9 are less than those previously calculated, even though irrigated areas have substantially increased. The primary reason for the differences in return flow estimates is the irrigation return flow factor. On a statewide basis this reflects the sum effects of irrigation method, water management, predominant soil types, crops and a host of other factors.

Irrigation Return Flow Water Quality Problems in the Great Plains

The Water Resources Council (U.S. Water Resources Council, 1978) recently assessed water problems and the significance of these problems in various areas of the United States. Erosion was shown to be the prevalent problem in only limited areas of the Great Plains, with the most serious erosion existing in the southwest portion of the region. Other areas of serious erosion exist in both North Dakota and South Dakota. The Council report did not determine how much of the erosion is related to irrigation activities.

A survey conducted by Great Plains' 208 planners and irrigation experts helped determine the extent of irrigation-related pollution problems. Results of this survey are summarized in Table 10. Disagreements exist regarding the influence of irrigation activities on the identification of pollution problems associated with IRF, although such problems are in evidence.

The scale of irrigation related nonpoint source pollution of surface water supplies by sediments and nutrients, and groundwater pollution by nutrients within the irrigated areas of the Great Plains, has not yet been fully determined. Irrigation in this region is extensive, with more agricultural chemicals being applied as irrigated areas expand. There exists the probability of significant degradation of the water quality of IRF through over-fertilization and misuse of irrigation water. Expanded irrigation development on coarse-textured soils represents a special IRF pollution hazard because of the low water-holding capacity of sandy soils. Over-irrigation or rainfall immediately following an irrigation can result in leaching of soluble pollutants.

An estimate of the impact of current practices, showing the extent and magnitude of pollution problems from irrigation by regional case histories, is presented in the following paragraphs. Information in these histories may or may not apply to specific situations confronting users of this manual.

TABLE 10. IRRIGATION-RELATED POLLUTION PROBLEMS IN THE GREAT PLAINS STATES [1/]

State	Potential pollution problems from irrigation return flows		Most probable pollution problems
	208 Planners	Irrigation Experts	
Colorado	High priority in the South Platte and Arkansas river basins.	Groundwater for irrigation is important. Low water-holding capacity of sandy soils and shallow water table along the Platte are problem areas.	Sediments and nutrients in Larimer and Weld Counties; 66 percent of sediment loads and 55 percent of nitrate-nitrogen contribution to surface and groundwater attributable to irrigation.
Kansas	Yes, but unsure of priorities and areas.	Local groundwater quality problems especially in parts of Harvey, Reno, Stafford, and Pratt Counties. Water quality degradation due to irrigation is limited.	Salts and sediments in western Kansas. Salinity problems along the southern border of southwest Kansas. Potential problems with agrochemicals.
Montana	Medium priority in all areas but mountainous.	Irrigation is not a major polluter. Some minor problems in Lower Yellowstone Valley with return flows.	Sediments. Excess nitrogen leached from irrigated sugar beets and corn.
Nebraska	Medium priority, although return flow is only rated 6th (out of 12 problems) in priority. Central Platte, North Platte Rivers and Loup and Republican Rivers identified as problem areas.	Irrigation pollution is very minimal. In areas of shallow sandy soils and high water table, NO_3 may be leached to groundwater. By Nebraska law, irrigators pumping groundwater cannot let water run off. Runoff from surface water projects is small. Rainfall is greater pollution hazard than IRF.	Nitrates.
New Mexico	Lack of data produces a disagreement.	Pollution problems in the shallow groundwater sources. Ogallala groundwater tends to be of good quality.	Nutrients from septic tanks are suspected. Nitrates where water table is shallow and soils are sandy.
North Dakota	Low priority.	By nature of irrigation practices, irrigation assigned a minimal value. Occasionally sediment problems along lower reaches of Yellowstone River basin in William and McKenzie Counties.	Sediments, if any.
Oklahoma	Only scattered areas are of high priority, not statewide.	Groundwater quality is good. Very minor.	Unidentified. Salinity in aquifer of Harmon County. Sediments.
South Dakota	Low to medium priority.	Contamination of groundwater identified in eastern South Dakota where aquifers are relatively shallow.	Salts.
Texas	Not with return flows. Different areas, but not specifically identified.	Only localized areas. Pollution caused by individual wells in localized areas.	Salts. Nitrates where soil is sandy and water table shallow.
Wyoming	High priority in some areas.	Surface water quality generally good. Poor groundwater quality found primarily in northeastern Wyoming.	Nutrients and salts.

[1/] Per. com. with Great Plains 208 planners and irrigation experts.

Central High Plains--

Colorado--A survey of 270 irrigated farms in central and eastern Colorado showed that residual nitrate-nitrogen (NO_3-N) can accumulate in the soil profile (Ludwick, et al., 1976). This nitrogen can then be leached by precipitation or the initial irrigations of the following season and moved to receiving waters. A water quality management study, authorized under Section 208 of P. L. 92-500, found that irrigated agriculture was the major contributor to water pollution in Larimer and Weld Counties, Colorado (Larimer-Weld Regional Council of Governments, 1977). Irrigation contributed 66 percent of the sediment loads, 95 percent of the total dissolved solids (TDS), and 55 percent of the nitrogen found in both surface water and groundwater. Irrigation discharges to streams were eight times larger than discharges from other water sources. However, sediments in receiving streams did not present a serious problem.

Kansas--A Kansas water quality study (supported in part with Section 208 funds) concluded that IRF is a small part of the possible water quality effects associated with irrigation (Balsters and Anderson, 1978). Surface return flows from irrigation may be a problem in areas along the Arkansas River and in the organized irrigation districts of northcentral Kansas. On the state's upland irrigated areas, in most cases, little irrigation runoff reaches the water courses. The authors go on to say, however, that nitrogen contamination of shallow aquifers may become a problem because of the increased use of tailwater pits. Problems of brackish groundwater contaminating adjacent heavily-pumped aquifers have occurred in parts of the Republican River basin, the Equus Beds north of Wichita, and the Great Bend Prairie region south of Great Bend.

Montana--Limited research data on irrigation-related nonpoint source pollution are available from Montana. Sediment is the major pollutant when a problem does occur. Irrigation return flows have better quality than the applied water, due to the filtering effect of the soil. Although it has not been quantified, excess nitrogen is believed to be leached from lands planted to sugar beets and corn. The leached nutrients, however, do not constitute a pollution problem in the river waters (G. Westesen, per. com.).

North Dakota--Irrigation is not considered a major contributor to nonpoint source pollution due to: (1) the small percentage of land under irrigation; (2) the lack of concentration of irrigated areas; and (3) the water quantities applied are often equal to, or less than, seasonal ET. Little opportunity exists for mass emission of sediments and nutrients. Surface irrigation is practiced along the lower reaches of the Yellowstone River and sediment loads occasionally are recognized as a pollution problem. Soils in this area are fine-textured and readily erodable (J. Bauder, per. com.).

Nebraska--Considerable investigation has been done on determining the extent of groundwater contamination of the Ogallala Aquifer. For example, nitrate-nitrogen concentration increased from 2.5 to 3.2 ppm during 1976, a 29 percent increase in the state average (Olson, 1976).

Nitrate leaching losses from irrigated sandy soils appear to be the prime contributor to continued nitrate build-up in two areas of Nebraska. Studies have shown nitrate distributed throughout the soil profile, from the soil surface to the water table, after 10 years of irrigated corn on sands (Muir, et al., 1976; Boyce, et al., 1976).

The growing of irrigated corn on coarse-textured soils and the widespread use of N-fertilizers can result in the leaching of NO_3 to the groundwater. It has been estimated that 50 percent of the commercial N-fertilizers used in Holt County (located in the eastern part of Subarea 1015) leach to groundwater (Exner and Spalding, 1979). Exner and Spalding (1979) estimated an average increase of 1.1 ppm of NO_3-N per year as representative of the irrigated region which they studied. This average could well represent other areas of the Sandhills that are intensively irrigated.

Southern High Plains--

New Mexico--Irrigation in the High Plains of New Mexico constitutes only about 10 percent of the total land use. Limited research indicates that irrigated agriculture is a minor water polluter when compared to other pollution sources, with nitrates being the primary problem. Saline groundwater is a serious problem in the Mesilla Valley of the Rio Grande River, which lies outside the Irrigated Great Plains.

A study by Taylor and Bigbee (1973) indicated a relationship between irrigation season and nitrate content in the groundwater in the High Plains. Soils in the High Plains are fine sandy loams to loams. Agricultural areas where little or no N-fertilizer was used had low NO_3-N in the groundwater, regardless of water use. Differences in the peak of NO_3-N concentrations during different times of the growing season were related to the presence of coarse-textured soils. The poor water quality of the groundwater in this region was attributed in part to the large use of nitrogen fertilizers on the coarser soils.

Texas--A situation similar to that found in the High Plains of New Mexico exists in the irrigated High Plains of Texas. The groundwater supply in specific areas of the rolling plains where the soil is sandy and the water table is shallow are susceptible to nitrate increases. This will most likely occur when high N-fertilizer applications are immediately followed by heavy rainfalls or irrigations.

Reeves and Miller (1978) examined the distribution of NO_3-N, Cl^-, and Total Dissolved Solids (TDS) in the groundwater of west Texas. Both coarse-textured and fine-textured soils exist over the groundwater table in this area. High nitrate values caused primarily by deep percolation of nitrogen fertilizers occur in the groundwater in intensively-cultivated areas having sandy soils (Table 11). The coarse-textured soils were identified with the regional pattern of poor quality groundwater. Note that Hale County, the most intensively-irrigated county in the entire Irrigated Great Plains as of 1976, showed a decrease in NO_3-N over the period 1951 to 1970.

TABLE 11. INCREASES IN NITRATES IN OGALLALA GROUNDWATER IN WEST TEXAS COUNTIES HAVING DIFFERENT SOIL TYPES [1]

County	Dominant soil type in county	NO_3-N in ppm 1951	1970	Increase
Dawson	Sandy	2.9	9.9	7.0
Hockley	Sandy	0.5	1.6	1.1
Terry	Sandy	1.8	5.2	3.4
Crosby	Fine-textured	1.1	1.1	0
Hale	Fine-textured	0.7	0	-0.7
Parmer	Fine-textured	0.5	0	-0.5
Swisher	Fine-textured	0	0	0

[1] Modified from Reeves and Miller, 1978.

EFFECT OF CURRENT IRRIGATION MANAGEMENT PRACTICES ON IRRIGATION RETURN FLOWS

Irrigation System Management

Irrigation Methods--

Irrigation water is applied by three basic methods--surface, sprinkler, and trickle-drip. The systems most commonly used in the Great Plains are illustrated in Figure 16. Each irrigation method has its own characteristics which make it more desirable or less desirable for a given location. Technical information describing the design, operation and use of irrigation systems is available from a variety of publications (Merriam, 1968, 1977; Stegman, et al., in prep.; Fischbach, 1975; Westesen, 1977). These publications should be consulted for the advantages and limitations of each irrigation system when used in particular locations.

Surface systems--The most widely-used irrigation systems in the Great Plains are surface systems. In surface irrigation, water flows by gravity from the upper end to the lower end of a field. The simplest and cheapest method is wild flooding, when water is allowed to flow out of the irrigation ditch and over the field. When row crops with furrows are present, better control is obtained with siphon tubes to transfer water in the open-ditch system to either furrow or border irrigated fields. The main characteristic

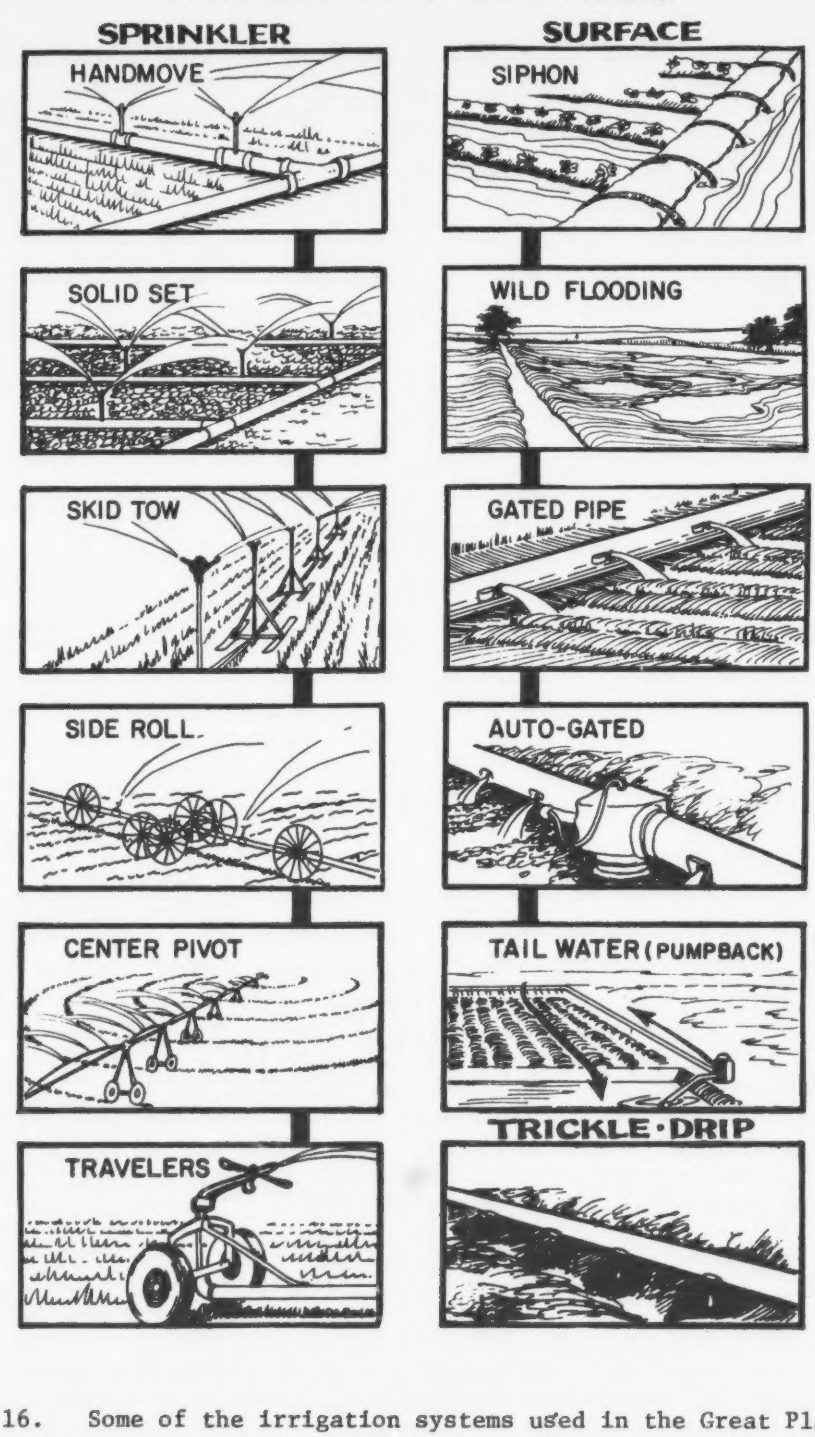
IRRIGATION SYSTEMS
SPRINKLER
SURFACE
HANDMOVE
SIPHON
SOLID SET
WILD FLOODING
SKID TOW
GATED PIPE
SIDE ROLL
AUTO-GATED
CENTER PIVOT
TAIL WATER (PUMPBACK)
TRICKLE · DRIP
TRAVELERS

Figure 16. Some of the irrigation systems used in the Great Plains.

of these systems is that the rate of applied water entering the soil profile is primarily determined by the physical properties of the soil.

Gated-pipe systems, a form of surface irrigation, move water to the field more efficiently than open ditches. These systems require only small pressure heads in the pipe system to distribute water. Gated-pipe is adapted to field slopes of one percent or less for soils with medium-to-low infiltration rates. These systems can be used on land slopes up to two percent in areas where soil erosion from summer rainfall is not a problem. Gated-pipe irrigation systems can be adapted to apply water automatically. This reduces the pipe handling, decreases labor cost and time, and improves the efficiency of water application.

The water which runs off and collects at the lower end of a surface irrigated field (tailwater) can be recaptured and reused by way of tailwater reuse systems. Only a small amount of pumping is needed to return and reuse tailwater in the irrigation system.

Sprinkler systems--Sprinkler irrigation systems have proven to be versatile methods of applying water, especially where surface methods cannot be used due to excess slope or very sandy soils. Sprinkler systems substitute capital and energy for the more intensive labor required with surface methods. Sprinklers are well adapted to many soils and to fields with steeper slopes or irregular topography. However, one type of sprinkler system may work well on a particular field while another type of sprinkler system may not. Sprinkler systems, as do other irrigation methods, require careful matching with soil type, climate and crop conditions.

Sprinkler systems can be classified as moved or moving types of systems. Moved sprinklers--handmove, solid set, skid-tow and side-roll--apply and distribute water from a fixed point during the irrigation cycle. Moving sprinklers--center pivots and travelers (big guns and booms)--move as they apply and distribute water during the irrigation cycle. Whether a system is moved or moving affects the irrigation design for the field, as well as system capability to control the amount of water application.

The irrigation pipes of hand-moved irrigation systems are hand-assembled for a single irrigation cycle. After the irrigation, the pipes are disassembled and moved to the next fixed irrigation location. The area to be irrigated with solid-set systems is covered with a grid of pipes and sprinklers which are not moved until the end of the irrigation season. Permanent sets are solid sets with buried pipes which are not moved at all.

The skid-tow sprinkler systems consist of rigidly coupled laterals connected by a flexible joint to a main line, which is usually positioned in the center of the field. The laterals are towed end first over the main line from one side of the field to the other by a tractor. Outriggers keep the lateral upright.

Center pivot sprinkler systems are self-propelled moving lateral pipes which pivot around a central point. The pipes are suspended on towers supported by wheels, which are automatically propelled by pneumatic, mechanical, hydraulic, or electric power. These systems irrigate circular areas of about a 400-meter diameter, or about 52-57 hectares. A simple large sprinkler mounted on a trailer constitutes the traveler irrigation system. This sprinkler covers 3-4 hectares during a set. A motor connected to a cable pulls the sprinkler across the field. A flexible hose is required to supply water to the sprinkler from the pumping point.

Trickle-drip systems-- Trickle (drip) irrigation allows greater control than most other methods. It provides a very slow application of water directly to the soil surface through pipes lying on or beneath the soil. Normally, water is released through orifices or emitters, porous tubing, or perforated plastic tubing operating under low pressures. A small but constant amount of water can be applied frequently to a limited area of the soil surface.

Water Management--

Irrigation water management is the timing and regulating of water applications to satisfy both the crop water-use requirement and the leaching required to maintain the salt balance without causing excess nutrient leaching or erosion. Information on when to irrigate a given soil and crop is available from a number of sources (Christensen and Westesen, 1978; Eisenhauer and Fischbach, 1978; Merriam, 1977, 1978; Schneider, et al., 1976; Stegman, et al., in prep.). However, basic water management procedures must be understood before management schemes which minimize pollutants in IRF can be created.

Water management encompasses the timing of the irrigation, the amount of water applied, the uniformity of application, and the rate of application. Efficient application and uniform distribution of water are extremely important in minimizing the problems addressed by this manual. Water application efficiency [the ratio of: (1) the water beneficially used to supply the crop requirement or maintain a favorable salt balance to, (2) the gross water application] depends on the type of irrigation system and its ability to uniformly and timely apply water. Water application efficiencies have been discussed by several authors (e.g. Kruse and Heermann, 1977; Kruse, 1978; and Merriam, 1977). Typical values are given in Table 12.

The relative irrigation efficiencies of sprinkler and surface systems can be misleading. If a sprinkler system is compared with a surface system, (gated-pipe, for example) on a shallow coarse-textured soil or on a steep land slope without a tailwater reuse system, the sprinkler system would be much more efficient. However, if the sprinkler system is compared with a surface system (gated-pipe with reuse) on a medium-textured soil with a one percent slope or less, the opposite could be true.

TABLE 12. ESTIMATED IRRIGATION APPLICATION EFFICIENCIES FOR IRRIGATION SYSTEMS [1]

Irrigation system	Suggested efficiency	Range of efficiencies
	- - - - percent	- - - -
Surface		
Open ditch with no reuse	50	30-70
Open ditch with tailwater reuse	65	45-80
Gated pipe with tailwater reuse	70	60-80
Autogated with tailwater reuse	85	80-90
Sprinkler		
Handmoved	70	70-75
Solid set	75	65-80
Skid tow	75	65-80
Side roll	75	65-80
Center pivot	80	70-85
Travelers (Big Gun)	75	65-80
Trickle-drip	90	85-95

[1] Fischbach (ed.), 1977.
The efficiencies are based on proper irrigation management and design.

One of the best ways of improving water management is through the use of irrigation scheduling techniques (Jensen, 1975). These techniques stress the application of the correct amount of water at the right time to obtain maximum crop production, regardless of the application method. Irrigation scheduling also can consider the probability of rainfall and allow for proper soil-water storage to reduce deep percolation losses.

The effect of current water management practices on soil-water losses in southwest Nebraska was surveyed by Watts, et al., (1974). The data on applied water and losses for 35 corn fields with surface or sprinkler systems are summarized in Figure 17. Total water application ranged from 16 to 67 cm, while water losses ranged from 0 to 38 cm. Most irrigation losses occurred when the total applied water (irrigation + rainfall) exceeded 57 cm. Rainfall immediately after an irrigation or excessive irrigation produced losses, even when seasonal water application was less than seasonal crop water use. Although most of these losses were through deep percolation, some can be attributed to surface runoff. Losses from surface irrigation averaged 16 cm out of the average 42 cm applied while losses from the center pivot system averaged 5 cm out of the 35 cm applied.

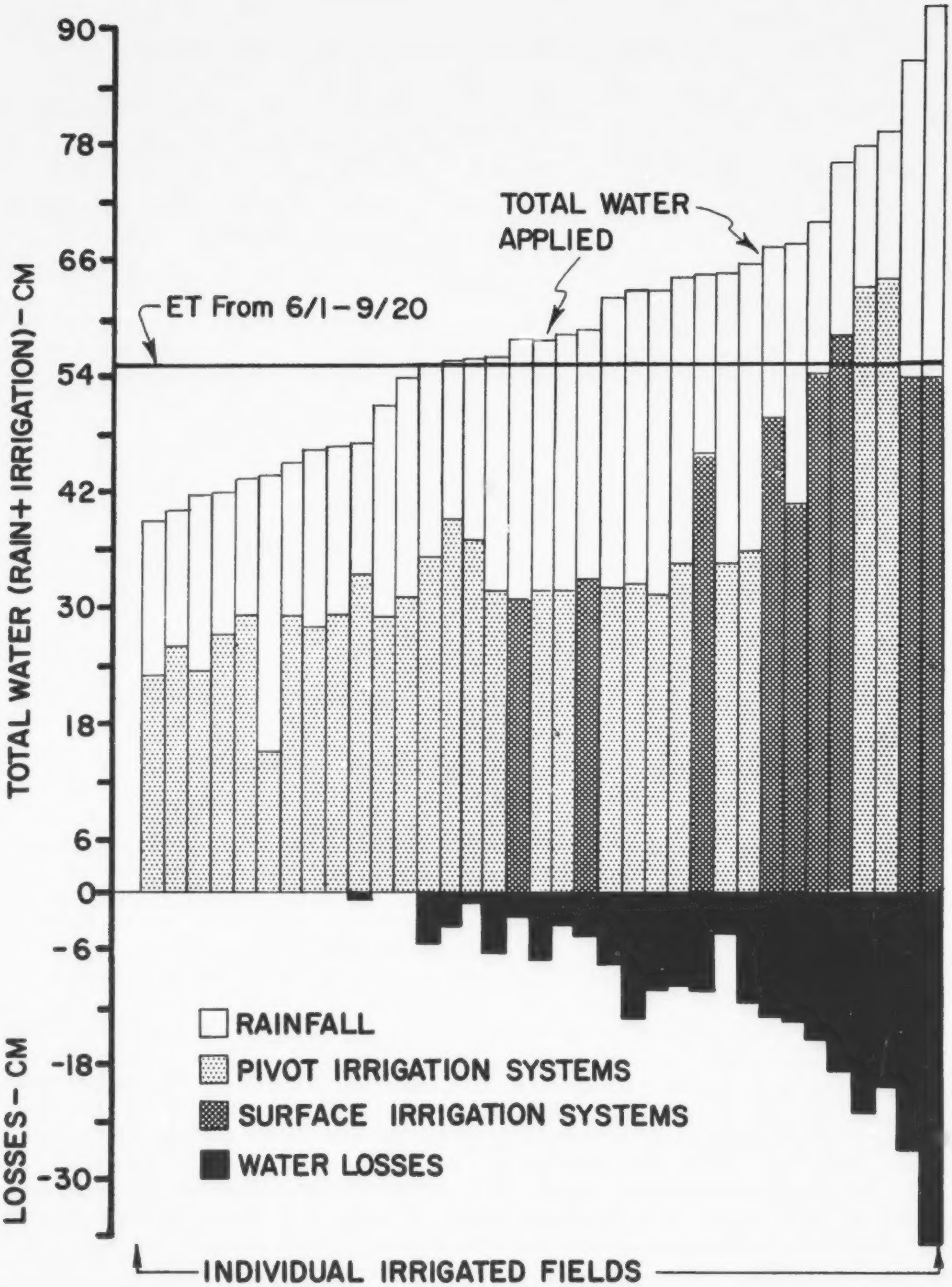

Figure 17. A summary of deep percolation water losses in 35 fields irrigated by either center-pivot or surface irrigation systems. (Watts, et al., 1974).

Crop water requirement--Crop water requirement depends on the climate and the crops grown. Different crops need different amounts of water, depending on the length of the growing season and which part of the plant is harvested as a crop (Table 13). The amount of water applied in any irrigation management program should ultimately depend on how much water a particular crop removes from the soil.

TABLE 13. GENERAL MAGNITUDE OF IRRICATION WATER AMOUNTS (SEASONAL) AS PRACTICED FOR FIVE CROPS IN THE GREAT PLAINS [1]

Crop	Seasonal water applications Average	Low	High
	- - - - - - -	cm	- - - - - - -
Alfalfa	62	25	114
Corn	57	27	82
Cotton	52	32	82
Sorghum	49	30	89
Soybeans	35	27	40

[1] Based on Fed. Energy Adm. and U.S. Dept. of Agr., Energy and U.S. Agriculture: 1974 Data Base, 1977.

In Nebraska, Wilson, et al., (1978) limited the amount of applied water below ET demands during some stages of corn growth without substantial yield reductions during an irrigation season having 12.5 cm of rainfall. The plants were under a small but continuous stress during the vegetative stages of growth in a climatic region where daily water-use demand was not extreme. In terms of yield per amount of water available (water-use efficiency), corn produced most efficiently when irrigated during the pollination and grain-filling (maturation) stages. As much as 12 cm of water was saved with no yield reduction. However, limited irrigation applications which result in reduced crop evapotranspiration especially during critical growth stages (such as the pollination period of corn) as well as in high water demand periods, will result in reduced crop yields.

Management schemes for limited irrigation in varying climatic situations may also be used for other crops (Garrity, 1979). Grain sorghum showed less overall sensitivity to the critical timing of water applications as compared to corn. Use of limiting water management schemes for other crops (New, 1977; Stewart, J. I., et al., 1975) can mean less surface runoff and deep percolation losses. Such schemes must be carefully applied, however, to avoid economic losses for the producer.

Water application rates--The rate of water application affects surface water runoff; the greater the intensity exceeds the soil infiltration rate, the greater the water runoff. High intensity irrigation rates can destroy aggregates at the soil surface, sealing the surface and reducing the infiltration rate.

It is generally easier to control application rates using sprinkler systems as compared to surface irrigation systems. With the latter, water must be applied at rates greater than the soil intake rate in order to advance down field. For example, the stream size at the head of a furrow must be sufficient to meet the irrigation requirements along the entire furrow length. Yet, the stream size should be kept as small as possible to keep the soil losses at a minimum. The maximum stream size depends on the size, shape, and slope of the furrow. From a soil-loss standpoint, the stream size on medium-textured soils should not exceed the value given by:

$$q = \frac{0.63}{S} \tag{2}$$

where q is the maximum nonerosive stream size, liters per second; and S is the field slope, in percent.

Sediment losses--Normally, 20 to 40 percent of the water applied by surface irrigation systems becomes surface runoff. Sediment loss decreases as the irrigation efficiency increases (Table 14).

TABLE 14. EFFECT OF SURFACE IRRIGATION APPLICATION EFFICIENCY ON SEDIMENT YIELD [1]

Irrigation application efficiency [2]	Sediment losses
percent	metric tons/ha
30	1.30
40	0.44
50	0.25
70	0.10
80	0.07

[1] Fitzsimmons, et al., 1977. Portneuf silt loam soil with slopes varying from 0.8-1.2 percent. Table is a summary of irrigations performed in 1975 and 1976.

[2] Percentage of applied water which is retained on the field.

Sediment losses vary not only during the irrigation event, but also during the irrigation season. They tend to be higher at the start of the irrigation season when the soil surface has recently been tilled and the crop cover is sparse (Table 15).

TABLE 15. RELATION OF SEDIMENT YIELDS FROM ROW CROPS DURING THE IRRIGATION SEASON [1]

Irrigation number	Sediment levels [2] In applied water	 In runoff water
	- - - - - - - - - mg/l	- - - - - - - - -
1st	41	2,020
2nd	76	946
Last	124	142

[1] Regional Planning office for Big Horn Basin 208 Policy Board, 1978.

[2] Concentrations after a 400-meter length of run.

Impact of Water Management on Pollution from Irrigation Return Flows--

The impact of current water management practices on water quality problems resulting from irrigation return flows is difficult to determine because of the lack of specific data. A schematic relationship of the influence between level of water application management and the expected level of IRF pollutants is shown in Figure 18. The amount of pollutants in IRF is dependent on the quantity of water applied and the level of water management skills used in operation of the irrigation system.

Soil Management--Although most erosion from irrigated lands in the Great Plains is caused by precipitation, irrigation can contribute to erosion, especially on steeper slopes. When water is applied directly to the surface, as with surface systems, irrigation can generate large quantities of sediment within the system. Practices which (1) control surface water runoff by reduction of runoff velocity; (2) increase water storage at the soil surface; or, (3) increase soil surface infiltration rates will reduce the amount of soil loss. These practices are discussed in the following publications: Stewart, B. A., et al., 1975; Lane and Gaddis, 1976; Walter, et al., 1977; McDowell, et al., 1978; Harmon and Duncan, 1978.

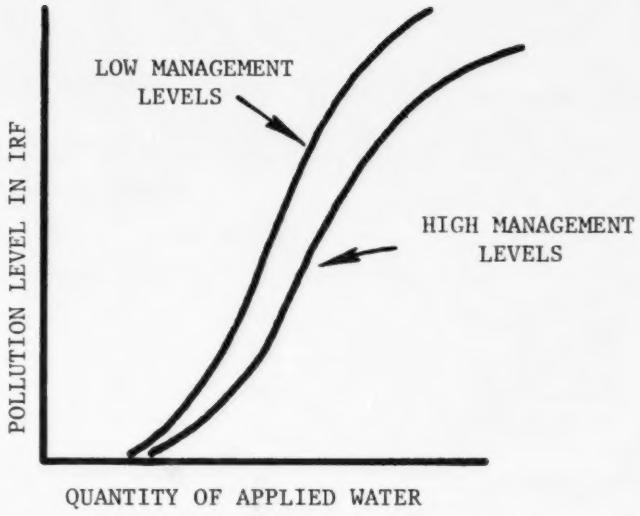

Figure 18. Schematic relationship between irrigation management levels and the degree of pollution in irrigation return flows. (Modified from Vlachos, et al., 1978).

Land Slopes--Land slope directly influences the amount of soil loss which takes place under irrigation systems (Table 16). Considerable sediment

TABLE 16. EFFECT OF LAND SLOPE FROM SURFACE IRRIGATION FIELDS ON GROSS SEDIMENT LOSSES [1]

Land slope	Soil losses [2]
percent	metric tons/ha
0.8	-0.3 [3]
1.0	1.6
1.2	1.6

[1] Fitzsimmons, et al., 1977.
Portneuf silt loam soil with slopes varying from 0.8-1.2 percent.
Table is a summary of irrigations performed in 1975 and 1976.

[2] Sediment losses during the initial irrigation.

[3] Deposited on lower end of irrigation field, no sediment removed from the field itself.

losses can occur when surface systems are used on lands having slopes exceeding one percent (Carter and Bondurant, 1976). Medium-textured soils on steeper slopes have twice the potential for sediment loss as coarse-textured soils. The greatest danger of erosion resulting directly from irrigation application exists where surface irrigation systems are used on steep slopes. Land leveling and land forming operations can successfully decrease erosion from the steeper, surface-irrigated fields. Where land slopes are too steep and land leveling is impractical, the use of sprinkler systems may be required as a means of reducing erosion.

Conservation practices--Crop management systems can greatly affect the magnitude of soil erosion and sediment losses (Table 17). Although these data are a summary of calculated soil losses from nonirrigated crop lands, the magnitude of these losses will most likely be representative of rainfall-caused losses from irrigated fields in higher rainfall areas of the Great Plains.

TABLE 17. SEDIMENT DELIVERY TO STREAMS FROM A RANGE OF SOIL TYPES FROM REPRESENTATIVE FARMS FOR THREE CROP MANAGEMENT SYSTEMS IN IOWA [1]

Crop management system	Soil erosion on farm site	Soil erosion which is delivered to stream	Actual sediment delivered from farm site
	metric tons/ha	percent	metric tons/ha
Conventional crop management with no crop residue	28	38	10.7
Contouring with 2.8 metric tons of residue	15.5	38	5.9
Terracing with 2.8 metric tons of residue	7.4	7	0.5

[1] Harmon and Duncan, 1978.

Tillage practices can have a large effect on soil losses (Table 18). Estimated soil losses may range three-fold from no-till to maximum tillage systems (Lane and Gaddis, 1976). Aarstad and Miller (1978) emphasized that the runoff water passing through the residues in the disked and till-planted furrows was often less turbid than the incoming irrigation water. Even with large irrigation water streams, the residue reduced soil losses when compared with clean tillage furrows.

TABLE 18. SOIL LOSS FROM IRRIGATION FURROWS AFTER 7 AND 24 HOURS OF IRRIGATION, AS AFFECTED BY TILLAGE CORN RESIDUE TREATMENT [1] [2]

Tillage treatment	Soil loss	
	1975 [3]	1976 [4]
	- - - metric tons/ha·day - - -	
After 7 hours:		
Clean tillage	1.53	0.4
Disked [5]	0.09	0.04
Till-plant [5]	0.02	0.02
After 24 hours:		
Clean tillage	0.89	1.3
Disked [5]	0.06	0.2
Till-plant [5]	<0.01	0.1

[1] Aarstad and Miller, 1978.

[2] Fine sandy loam soil with 3 percent slope, second irrigation of the season.

[3] Average of 2 replications.

[4] Average of 8 replications.

[5] 3.5 metric tons/ha corn residue on surface before disking or planting.

In general, soil losses vary inversely with crop residue cover. Tillage systems which leave crop residue on the soil surface, especially at the beginning of the irrigation season, reduce erosion and water runoff. Proper conservation tillage systems, especially with surface irrigation methods, can considerably reduce sediment losses in tailwater during the early part of the irrigation season.

Sediment losses from irrigated fields can be reduced by utilizing one or more of the following procedures: irrigation systems can be modified or changed, fields can be leveled, tillage operations can be reduced, or vegetative filter strips and sediment ponds can be installed (Fitzsimmons, et al., 1977; Lindeborg, et al., 1977; Stewart, B. A., et al., 1975; Harmon and Duncan, 1978). Examples of the effectiveness of these methods to reduce sediment losses is shown in Table 19. Sediment in the tailwater of surface systems can be filtered out as it passes through a grass strip or other close-growing crop or through the use of sediment ponds. Runoff and sediments from steeper slopes or undulating topography can be reduced through the installation of properly designed sprinkler systems.

TABLE 19. EXPECTED REDUCTION OF SOIL SEDIMENT LOSS WITH SELECTED IRRIGATION MANAGEMENT PRACTICES [1]

Management practice	"Typical" sediment loss retained on farm [2]
	percent
Sprinkler irrigation [3]	100
Mini-basin [4]	90
Sediment pond [5]	67
Grass or grain strip [6]	50
Flow cut-back [7]	30

[1] Lindeborg, et al., 1977.

[2] In this study conducted in the Magic and Boise Valleys of Idaho, "typical" assumes current management practices on silt loam soils with slopes from one-half to four percent.

[3] The 100 percent retention of sediment loss occurs when runoff is reduced to zero. This would be true only if the water application rate is less than or equal to the soil intake rate.

[4] Mini-basins are shallow ponds constructed at the end of the field to retain tailwater runoff.

[5] Sediment ponds are installed into the return waterway to decrease flow velocity and retain sediment.

[6] Grass or grain strips are planted at the lower end of the field to slow down tailwater and retain sediment.

[7] Flow cut-back means to reduce the streamsize of the surface irrigation set when the water reaches the end of the field. The reduced flow results in decreased erosion and soil transport.

Fertilizer Management

Much attention has recently been focused on the quality of irrigation return flow as influenced by fertilization practices in irrigated agriculture (Fried, et al., 1976; Pfeiffer, et al., 1978; Int. Garrison Diversion Study Board, 1976; Duke, et al., 1978; Hay and Black, 1978; Whitney, 1978; Balsters and Anderson, 1978; Regional Planning Office for Big Horn Basin 208 Policy Board, 1978). It is very difficult to isolate any single practice as being the major cause of water quality degradation. Water pollution associated with applications of nitrogen and phosphorus can be related in some degree to application rates. Excessive rates can increase the residual buildup of both nitrogen and phosphorus in the soil. The method of application, which is influenced by whether or not the fertilizer material is incorporated, as well as the time of application in relation to crop demand, also influence the occurrence of these nutrients in irrigation return flows. Additionally, the nitrogen source used (anhydrous ammonia, ammonium nitrate, etc.) is important. To further complicate the matter, there may be interaction between certain water and fertilizer management practices which may result in additional losses of nitrogen. These interactions are affected by yearly rainfall variation, root zone depths and soil texture. In spite of the complexity of the problem, it is clear that there is room for improvement in fertilizer management. Under certain conditions, these improvements can have a very positive impact on the quality of return flow.

Use of Fertilizers in the Great Plains--

Nitrogen (N) and phosphorus (P) are the major nutrients required in large amounts by the crops grown in the Great Plains. Potassium occurs naturally in high quantities in the majority of the Great Plains soils and does not normally constitute a fertilization problem. It may, however, be required on the more sandy soils. Micro-nutrient fertilizers, used in small amounts, do not appear to be a potential pollution source.

The average nitrogen and phosphorus fertilizer applications and the amounts removed by common crops in the Great Plains are shown in Table 20. Nitrogen applications usually are greater than the amount of nitrogen removed in the harvested portion of the crop. However, the amount removed from the soil varies greatly by type of crop or forage grown.

Numerous discussions exist about the behavior of nitrogen. This is because nitrogen is the most common and yet the most limiting nutrient in agriculture. An understanding of the cyclic behavior of nitrogen and its use for irrigated crop production is essential for evaluating nitrogen/water management practices. This cyclic nature of nitrogen in the soil-plant-water system is shown in Figure 19. Nitrogen movement, especially that of nitrate-nitrogen, through the soil is an important concern in irrigated agriculture. Differences in nitrate losses closely reflect the fertilizer and irrigation management practices used during the season. The amount of nitrate lost depends on: (1) the amount of nitrogen applied; (2) timing of individual applications; (3) amount and timing of water applications; (4) distribution of seasonal rainfall; and (5) soil texture. Discussions of the individual parts of the nitrogen cycle can be found in other publications (Frere, 1976; Porter, 1975).

The amount of phosphorus removed by crops is usually greater than that of the applied fertilizer. From the standpoint of crop production or water quality, the irrigation management of phosphorus is not as critical as that for nitrogen because most of the phosphorus is rapidly converted to an insoluble form which remains very close to the point of application.

TABLE 20. AMOUNT OF MAJOR NUTRIENT FERTILIZERS ADDED AND ESTIMATED NUTRIENT REMOVAL IN HARVESTED YIELDS OF IRRIGATED CROPS IN THE GREAT PLAINS STATES 1/

Crop	Harvested Yield 2/	Nutrients applied Nitrogen (N)	Nutrients applied Phosphorus (P_2O_5)	Nutrients removed 3/ Nitrogen (N)	Nutrients removed 3/ Phosphorus (P_2O_5)
	metric tons/ha	- - - - - - kg/ha	- - - - - - -	- - - - - - kg/ha	- - - - - - -
Corn (grain)	6.9	190	45	160	42
Sorghum (grain)	4.7	160	34	126	36
Cotton	1.1	60	38	53	28
Soybeans	2.4	12	22	130 4/	26 4/
Alfalfa	9.0	5	33	202 4/	45 4/

1/ Stewart, B.A., et al., 1975; Council for Agr. Science and Technology, 1975; and per. com.

2/ Average yields over Great Plains region.

3/ Estimated values for Great Plains.

4/ Nutrients removed are greater than the nutrients applied.

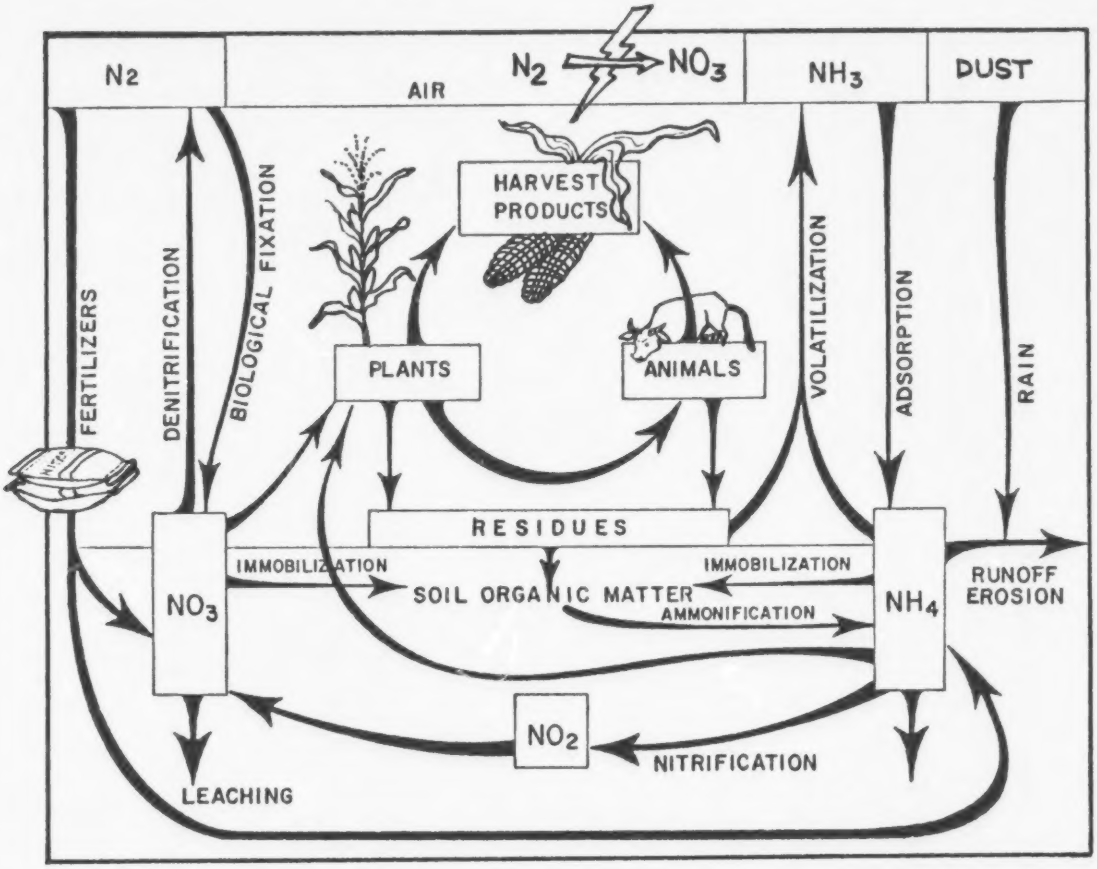
N2
AIR
N2
NO3
NH3
DUST
FERTILIZERS
DENITRIFICATION
BIOLOGICAL FIXATION
HARVEST PRODUCTS
PLANTS
ANIMALS
VOLATILIZATION
ADSORPTION
RAIN
RESIDUES
IMMOBILIZATION
IMMOBILIZATION
SOIL ORGANIC MATTER
AMMONIFICATION
NO3
NH4
RUNOFF EROSION
NO2
NITRIFICATION
LEACHING

Figure 19. Diagram of nitrogen cycle inputs into and outputs from soil-plant-water system. (Modified from Frere, 1976).

Nitrogen Losses and Fertilizer Management Practices--

The current existence of a few severe, localized NO_3-N pollution problems (especially in groundwaters) and the continued expansion of irrigation on sandy soils (where N moves more rapidly) indicate that an evaluation is needed of the impact different water and nitrogen management practices have on nitrate leaching losses (Smika, et al., 1977).

An example of the amount of nitrogen that can be lost from fertilizer applications is shown in Figure 20. Potentially leachable nitrogen increases rapidly when nitrogen applications exceed that required for maximum crop yields. Nitrogen will be recycled to the soil if the stover is left in the field. However, this nitrogen must be converted to the nitrate form (Figure 19) before it is subject to leaching. If nitrogen application does

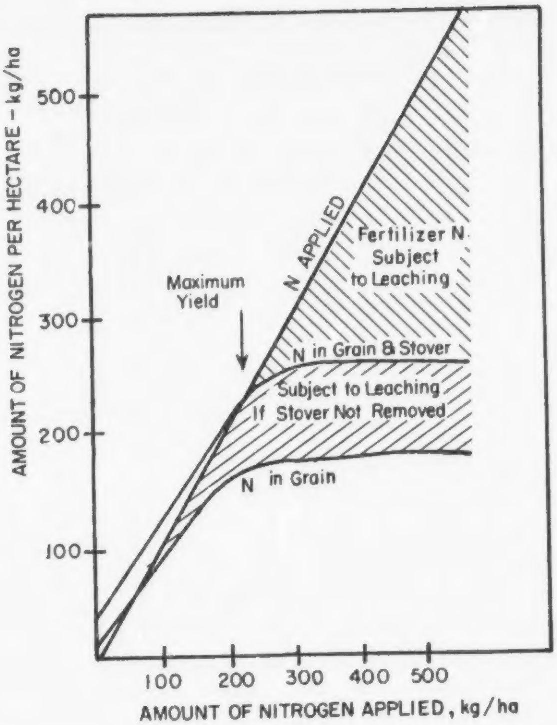

Figure 20. Effect of nitrogen fertilizer additions on potential leaching in irrigated corn. (Modified from Fried, et al., 1976).

not exceed crop needs, there will be little nitrate available for leaching. An exception may occur in sandy soils, where nitrogen applied early in the season may be leached below the root zone by early rain or excessive early irrigation (Watts, et al., 1978).

In practice, larger amounts of nitrogen fertilizers than required to meet crop needs are usually applied. This extra amount of nitrogen as nitrate is subject to leaching losses either by excessive irrigation or by rainfall. This, in turn, could increase the nitrate concentrations in ground and surface waters. The potential NO_3-N losses in deep percolation water for different nitrate concentrations and amounts of drainage water are given in Table 21. Because the concentration of NO_3-N in the soil or water alone is not always a good indicator of leaching losses, the total amount of percolating water also must be considered. Potentially, leaching of nitrates is greater in the coarse-textured soils than the fine-textured soils because the coarse-textured soils have more excessive water movement

TABLE 21. POTENTIAL NITRATE-NITROGEN LOSSES FOR COMBINATIONS OF DEEP PERCOLATION AND NITRATE-NITROGEN CONCENTRATIONS

Amounts of drainage water	Concentrations of NO_3-N in drainage water 10 ppm	20 ppm	50 ppm
ha·cm/ha	- - - - - - NO_3-N losses, kg/ha		- - - - - -
5	5	10	25
10	10	20	50
20	20	40	100
30	30	60	150

which results in greater total mass emission.

Proper timing of fertilizer application also is important in the reduction of nitrate loss. In coarser-textured soils, smallest losses will occur most years when nitrogen fertilizers are applied as close to the time of use by the crop as possible. Studies show that excess water (rain and/or irrigation) during the early part of the growing season can result in leaching of preplant N-applications so that the total uptake by the crop is reduced and N-uptake by the crop is delayed (Hergert, 1978; Smika and Watts, 1978; Watts, et al., 1978).

Nitrate leaching losses for three application methods on a sandy soil are presented in Figure 21. When the rainfall was below normal during all of the growing season or during the first one-third of the season, N losses for all three application methods were about the same and resulted mainly from early season leaching of residual NO_3 in the lower profile. Application method had an important effect only when the springtime rainfall was above normal, because the amounts of irrigation water were controlled. Deep percolation losses of some nitrates are unavoidable within the limits of the type of water management studied. Nitrate-nitrogen percolation could occur because rainfall occurred immediately after an irrigation or because particular rainfall events considerably exceeded the soil moisture holding capacity.

Similar conditions could apply to an early fall fertilizer application of nitrogen in areas where water movement through the soil profile frequently occurs, or in areas where water movement through the soil is infrequent and residual nitrate increases because nitrogen rates are not adjusted for residual nitrogen.

Residual nitrate buildup results from the gradual accumulation of annual fertilizer applications (Duke, et al., 1978; Ludwick, et al., 1976). Examples of residual nitrate are shown in Table 22. The accumulation of nitrate in the soil can be leached with winter or spring rains or with

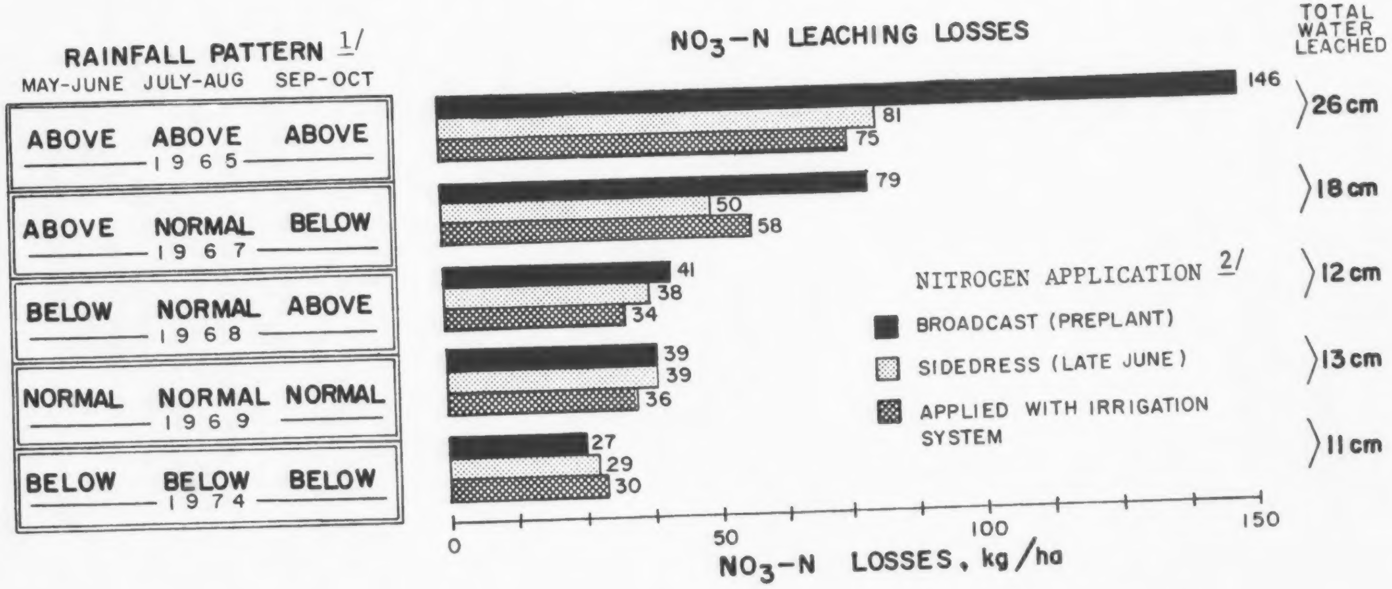

Figure 21. NO$_3$-N leaching and water losses for three nitrogen fertilizer application methods with different rainfall patterns. (Watts, et al., 1978).

1/ Rainfall patterns relative to normal for each one-third of growing season.

2/ For all methods:
(1) N applied of 246 kg/ha.
(2) Irrigation frequency = 4 days.
(3) Irrigate to replace ET minus rain during period.
(4) No irrigation unless at least 1.9 cm is required.

TABLE 22. RESIDUAL SOIL NITRATES AFTER FOUR YEARS OF FURROW IRRIGATION [1] [2]

Annual N applied	Total N accountable [3]	Residual soil nitrate [4]	Total nitrate in the soil profile [5]
kg/ha	- - - percent of applied nitrogen	- - -	kg/ha
0	--	--	19
67	75	0.7	21
134	75	3.0	35
202	63	3.4	47
269	51	4.9	73

[1] Ludwick, et al., 1976.

[2] Four furrow irrigations of 13 cm per irrigation in central and eastern Colorado on a clay loam soil.

[3] From determination of the total nitrogen balance of soil-plant system.

[4] Estimated NO_3-N remaining in the soil after 4 years of cropping.

[5] Total NO_3-N content in the upper 3 meters of the soil profile.

over-irrigation at the beginning of the next season. The nitrogen losses which occur during the winter or spring, especially on sandy soils, will be related directly to the amount of precipitation. Results of a recent study in the northern Great Plains suggest that nitrogen should not be applied in the fall on well-drained sandy soils since significant leaching could result (Bauder and Montgomery, 1979).

In general, nitrogen fertilizers should be applied as close to the time of use by the plant as possible for maximum use by the crop and minimum accumulations and losses. Light applications of nitrogen, managed to meet the needs of the crop during the growing period, tend to maintain lower nitrate concentrations in the soil solution within the root zone. Also, applications should be planned so that residual nitrate is minimized at the end of the irrigation season, providing reduced potential for leaching with winter precipitation. Nitrogen applications and leaching of nitrates for sprinkler-irrigated corn in North Dakota are shown in Table 23. When nitrogen fertilizer was applied at a one-time application of 168 kilograms (kg), the maximum amount of nitrate was lost. When this nitrogen application was split into three equal parts, the nitrate losses were reduced.

TABLE 23. NO_3-N LEACHING DURING CROP SEASON UNDER SPRINKLER-IRRIGATED CORN ON A MADDOCK FINE SANDY LOAM AT OAKES, NORTH DAKOTA [1]

Year	Nitrogen applied [2]	Amount of NO_3-N leached	NO_3-N concentration of leachate	Applied N leached as NO_3-N [3]	Relative Yield
	kg/ha	kg/ha	ppm	percent	percent
1977 [4]	22x1	2.2	5.4	9.9	70
	67x1	5.9	3.3	8.7	84
	168x1	40.1	63.5	23.9	100
	56x3	8.8	18.0	5.2	99
1978 [4]	22x1	4.0	3.2	18.0	48
	67x1	5.7	3.2	8.5	70
	168x1	25.2	12.5	15.0	91
	56x3	21.3	7.7	12.7	100

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[1] Bauder, et al., 1978.

[2] All nitrogen applied as NH_4NO_3. Single and first applications applied side-dress at planting. Split applications were broadcast applied. All treatments were applied to optimum irrigation plots.

[3] Amount of applied nitrogen leached below 1.5 meters.

[4] Irrigation totalled 42.2 and 33.7 cm for 1977 and 1978, respectively. The 1977 and 1978 seasons were quite similar, with 26.9 and 33.7 cm of rainfall, respectively. Individual irrigation applications were reduced from 6.4 cm in 1977 to 3.8 cm in 1978.

Nitrogen Losses and Irrigation Management Practices--

The previously-discussed factors become even more important when combined with irrigation water management practices. Because nitrate leaching is highly correlated with excess water application, improved control of water application is essential where nitrate leaching is a problem.

Wendt, et al., (1976) concluded that nitrogen remained in the root zone if the water applied was based on the potential ET only, regardless of the irrigation system or the criteria used to apply the water. When irrigation water was applied at twice the potential ET and fertilizer application was greater than 200 kg per hectare, leached water had excessive concentrations of NO_3-N. In Texas, the effects of sprinkler, furrow, and subirrigation systems on movement of band-applied fertilizer NO_3-N in a loamy, fine sand were generalized as follows: (1) under sprinkler irrigation, banded fertilizer moved downward from the point of application with some lateral movement as depth increased from rainfall and irrigation; (2) under furrow irrigation, the fertilizer tended to move toward the center of the bed and then downward, resulting in NO_3-N remaining in the upper portion of the soil profile longer than for the sprinkler system; and (3) under subirrigation, fertilizer moved upward and outward towards the furrows and then downward, resulting in higher concentrations of fertilizer in the upper profile for a longer time (Onken, et al., 1979). The influence of deep percolation water on NO_3-N losses under center-pivot irrigation systems on a coarse-textured soil in eastern Colorado is given in Table 24. Nitrate-nitrogen losses were proportional to the deep percolation of water. Duke, et al., (1978) state that the restriction of deep percolation of water to less than 3 cm per year holds N-losses to acceptable levels. However, such restrictions may be impossible in the more moist areas of the Great Plains.

TABLE 24. A THREE-YEAR SUMMARY OF THE INFLUENCE OF DEEP PERCOLATION LOSSES OF NO_3-N UNDER CENTER PIVOT IRRIGATION SYSTEMS IN NORTHEAST COLORADO[1/]

Deep percolation water	NO_3-N losses
cm	kg/ha
7.3	60
1.9	30
1.2	19
0.5	0.1

[1/] Duke, et al., 1978.

The practice of applying fertilizers with the irrigation water, called fertigation, yields the lowest amount of deep percolation nitrate losses.

Dylla, et al., (1976), showed an average increase in NO_3-N losses of 18 and 59 kg per hectare, respectively, for plots irrigated with 2.5 and 5 cm as compared to nonirrigated fertilized plots. Nitrogen fertigation with the 2.5 and 5 cm irrigation treatments, however, decreased the NO_3-N losses by 35 and 52 percent as compared to a single preplant application of granular N-fertilizer to the irrigated plots.

More efficient water management is required to minimize NO_3-N leaching losses on the coarse-textured soils. Studies in Nebraska (Watts, et al., 1978; Hergert, 1978) show that NO_3-N losses can be minimized in sandy soils through irrigation scheduling. Losses probably cannot, however, be reduced to zero. In years of normal rainfall, about 30 to 35 kg per hectare of NO_3-N may be lost with deep percolation of water during the growing season. When water percolation losses are 12 cm or less, NO_3-N leaching losses are essentially independent of the NO_3-N applied during the growing season and represent mainly leaching of the previous season's residual nitrate (Watts, et al., 1978).

Improved irrigation scheduling procedures are essential management tools when there is a risk of NO_3-N percolation losses. Specific recommendations for controlling both irrigation amounts and timing with proper N-fertilizer applications will lessen the potential pollution of NO_3-N in deep percolation.

Other Nitrogen Losses--

Nitrogen losses also are associated with sediments in surface water runoff. Typical results for soluble nitrogen components obtained with surface runoff studies are shown in Table 25. In terms of total mass emission losses, the amounts of nitrogen lost with organic matter and sediments suspended in the runoff water usually are much greater (depending on the amount of erosion) than those dissolved in the water. The total nitrogen loss and sediment loss are directly related. However, the amount of soil erosion and the total N lost can vary markedly amoung different soils and different tillage systems. Those tillage systems which reduce erosion also reduce nitrogen losses in the surface runoff (Table 26). The concentration of inorganic nitrogen in surface runoff from fields in Iowa ranged from 1-12 ppm, (0.1 to 11 kg per hectare) varying both among fields and among years within the same fields (Harmon and Duncan, 1978).

Phosphorus Losses--

Phosphorus loss is very small in comparison to nitrogen loss. Most of the phosphorus that appears in irrigation return flow is associated with the sediments in surface runoff. Phosphorus concentrations also tend to correlate with the available phosphorus in the surface soil. The loss is dependent on both the method of application and the placement. For example, losses of phosphorus from corn irrigated with gated-pipe systems on a silt loam in Nebraska were reduced by the placement of phosphorus fertilizer with chisels, which put it below the depth from which sediments would normally be removed by runoff (Cihacek, et al., 1974).

TABLE 25. NITROGEN LOSSES WITH SURFACE WATER RUNOFF DURING MAY THROUGH SEPTEMBER WITH THREE TILLAGE SYSTEMS [1] [2]

Tillage system	Water runoff	Erosion	Soluble nitrogen NH_4-N	NO_3-N	Total nitrogen in sediments
	cm	metric tons per ha	- - - kg/ha - - -		kg/ha
Conventional [3]	5.4	32	0.1	0.4	29
Till [4]	3.5	12	0.05	0.3	16
Ridge [5]	3.1	3.5	0.05	0.2	6

[1] Harmon and Duncan, 1978.

[2] Average of three growing seasons on 0.6-1.8 ha watersheds in continuous corn with 168 kg N-fertilizer per ha annual applications.

[3] Conventional tillage utilizes a moldboard plow that inverts the soil and totally incorporates residue into the soil.

[4] Till planting is a one-pass tillage and planting system that permits row cropping with limited soil disturbance. The till planter clears a shallow path through the row of the previous crop, moving plant residues out of the planting area.

[5] Ridge planting is a cropping system in which crops such as corn are planted on top of the ridge of the previous year's row. Crop residue accumulates in the furrow and helps delay runoff and control erosion.

Erosion primarily removed the top surface soil which contains the highest concentration of organic matter and which may be rich in phosphorus from fertilization. An example of phosphorus transported in surface runoff from precipitation on a nonirrigated field is shown in Table 27, which illustrates that losses from heavy phosphorus fertilization are higher, although losses were less for corn planted on level terraces primarily because of the reduction in runoff. Increasing the fertilizer rate from 39 to 97 kg P per hectare for contour-planted corn nearly doubled the phosphorus losses in the sediments.

Available evidence indicates that deep percolation of phosphorus is small and not a major source of pollution (Balsters and Anderson, 1978; Harmon and Duncan, 1978; Int. Garrison Diversion Study Board, 1976). The phosphorus concentration of soil solutions is low, ranging from 0.01 to 0.1 ppm. Consequently, fertilizer applications do not greatly increase the levels of phosphorus in percolating waters.

TABLE 26. AVERAGE NITROGEN LOSSES WITH WATER RUNOFF AND SEDIMENTS FROM VARIOUS MANAGEMENT SYSTEMS [1] [2]

Tillage management operation [3]	Water runoff	Erosion	Soluble nitrogen NH$_4$-N	Soluble nitrogen NO$_3$-N	Total nitrogen in sediments
	cm	metric tons per ha	kg/ha		kg/ha
Conventional [4]	14	49	0.3	1.4	75
Till [5]	12	33	1.7	1.1	51
Chisel [6]	14	28	1.5	1.3	50
Disk [7]	12	17	2.2	1.5	30
Ridge [8]	11	11	2.7	1.1	20

[1] Modified from Harmon and Duncan, 1978. Soil types were: Ida, Tama, and Kenyon.

[2] Runoff from simulated rain on small plots planted to corn with rows up and down the land slope. Rainfall was 20-21 cm.

[3] Each had an N-fertilizer application of 168 kg N/ha.

[4] Conventional tillage utilizes a moldboard plow that inverts the soil and totally incorporates residue into the soil.

[5] Till planting is a one-pass tillage and planting system that permits row cropping with limited soil disturbance. The till planter clears a shallow path through the row of the previous crop, moving plant residues out of planting area.

[6] Chisel plows operate at depths equal to or slightly deeper than moldboard plows. Chiseling loosens dry soils and leaves up to three-fourths of the residue at or near the surface.

[7] Disk harrows have been used as both primary and secondary tillage tools. They incorporate at least half of the plant residues into the soil with each pass of the disk.

[8] Ridge planting is a cropping system in which crops such as corn are planted on top of the ridge of the previous year's row. Crop residue accumulates in the furrow and helps delay runoff and control erosion.

TABLE 27. SURFACE RUNOFF, SOIL SEDIMENT YIELDS AND PHOSPHORUS LOSSES FROM WATERSHEDS UNDER THREE MANAGEMENT OPERATIONS [1/]

Management operation (applied phosphorus)	Water runoff [2/]	Sediment yield	Phosphorus losses Solution	Phosphorus losses Sediment
	cm	metric tons/ha	- - - kg/ha	- - -
Contour planted corn (97 kg P/ha)	8.1	25.0	0.17	1.05
Level terraced corn (97 kg P/ha)	0.9	1.3	0.05	0.08
Contour planted corn (39 kg P/ha)	6.8	17.0	0.11	0.58

[1/] Harmon and Duncan, 1978.

[2/] Total precipitation ranged from 76-78 cm.

Pesticide Management

Pollution resulting from pesticide use poses three questions:

(1) What types and amounts of pesticides are lost from agricultural fields?

(2) Can these losses be reduced by changes in management practices?

(3) Given a particular pesticide loss from a field, what is the most likely impact on the water quality of return flows and receiving waters?

Losses from pests in the United States probably average 30 to 40 percent of total production and would be even higher without pesticides. The use of pesticides has increased rapidly in the last decade because of their effectiveness and labor-saving features. Total farm pesticide use in the United States has increased 40 percent from 1966 to 1971, and 38 percent from 1971 to 1976 (Eichers, et al., 1978). In 1976, 70 percent of the pesticides used on crops in the Great Plains were applied to the five crops under consideration in this manual (Table 28). Of these, 58 percent were applied to corn. Herbicides and insecticides are the pesticides of most concern because these constituted 92 percent of total pesticide usage in major crops in the United States.

Specific herbicides and insecticides of major importance in these five crops in the Great Plains are listed in Tables 29 and 30. More

TABLE 28. PESTICIDES USED IN NORTH DAKOTA, SOUTH DAKOTA, NEBRASKA, KANSAS, OKLAHOMA AND TEXAS IN 1976 [1/]

Crop	Area planted ha (millions)	Herbicides		Insecticides	
		Percent of area treated	Quantity applied kg (millions)	Percent of area treated	Quantity applied kg (millions)
Corn	5.93	81	11.12	50	4.27
Sorghum	6.36	50	5.45	28	1.63
Cotton	2.12	68	1.27	30	1.09
Soybeans	1.22	51	1.09	9	0.09
Alfalfa	2.96	<1	0.05	11	0.45
Total pesticides used for five crops			18.98		7.53
Total pesticides used for all crops			26.2		10.9

[1/] Eichers, et al., 1978.

TABLE 29. MAJOR HERBICIDES USED IN NORTH DAKOTA, SOUTH DAKOTA, NEBRASKA, KANSAS, OKLAHOMA AND TEXAS IN 1976 1/

Herbicide	Major crop(s)	Quantity used
		kg (millions)
Atrazine	Corn and sorghum	7.1
2,4-D	Wheat, corn, and sorghum	7.0
Alachlor	Corn and soybeans	1.9
Propachlor	Corn and sorghum	1.7
Propazine	Sorghum	1.6
EPTC	Corn	1.3
Trifluralin	Cotton and soybeans	1.2
Butylate	Corn	1.0
Cyanazine	Corn	0.5
Dicamba	Wheat, corn, and sorghum	0.4
Total of above herbicides		23.7
Total herbicide used		26.0

1/ Eichers, et al., 1978.

TABLE 30. MAJOR INSECTICIDES USED IN NORTH DAKOTA, SOUTH DAKOTA, NEBRASKA, KANSAS, OKLAHOMA AND TEXAS IN 1976 1/

Insecticide 2/	Major crop(s)	Quantity used
		kg (millions)
Parathion	Sorghum, cotton, and corn	2.4
Carbofuran	Corn and alfalfa	2.0
Carbaryl	Corn and soybeans	1.7
Disulfoton	Cotton and sorghum	1.5
Dyfonate	Corn	0.7
Methyl Parathion	Cotton	0.6
Phorate	Corn	0.5
Malathion	Alfalfa and sorghum	0.4
Toxaphene	Cotton	0.2
Total of above insecticides		10.0
Total insecticide used		10.9

1/ Eichers, et al., 1978.

2/ See tables in Appendix B for trade names of insecticides.

comprehensive lists with information on trade names, transport, toxicity, mobility and persistence are found in Tables B-1 and B-2 in Appendix B.

The rates of pesticides applied to a crop range widely (Table 31) because application rate depends on the specific pesticide, the pest, the soil, and climatic factors. The specific application rate required for effectiveness is listed on each pesticide label for each crop and pest. Seldom is it advisable to depart from this rate and it is illegal to apply a dosage greater than that specified on the label.

TABLE 31. RATES OF AGRICULTURAL PESTICIDES APPLIED TO CROPS IN THE GREAT PLAINS [1]

Crop	Range of pesticide application Herbicide	 Insecticide
	- - - - - kg/ha	- - - - - -
Cotton	0.6-4.7	0.5-13.6
Sorghum	0.9-1.8	0.3- 0.5
Soybeans	0.9-1.4	0.1- 0.2
Corn	1.2-1.9	0.7
Alfalfa	<0.1	<0.1

[1] Fed. Energy Adm. and U.S. Dept. of Agr., Energy and U.S. Agriculture: 1974 Data Base, 1977.

Processes Affecting the Fate of Pesticides--

Many factors affect the fate of pesticides in the environment, as shown in Figure 22. After application, adsorption to the soil largely influences other processes, especially leaching. The extent of adsorption is primarily determined by the properties of the pesticide and the soil. Pesticides leach more readily in sandy soils than in loams or clays or where organic matter content is low. Water-soluble pesticides leach more rapidly and readily than insoluble ones.

Persistence is the time span required to degrade a pesticide. In soil, this is largely a function of the pesticide, the rate of application, soil texture and organic matter content, and climatic conditions of which temperature and moisture are vitally important. Pesticides persist longer where organic matter is low and under cool, dry conditions. As persistence increases, the chance of a pesticide entering the runoff water increases; however, pesticide mobility and timing of the runoff event following the pesticide application are more important considerations. These latter factors, along with application rate, largely determine the pesticide

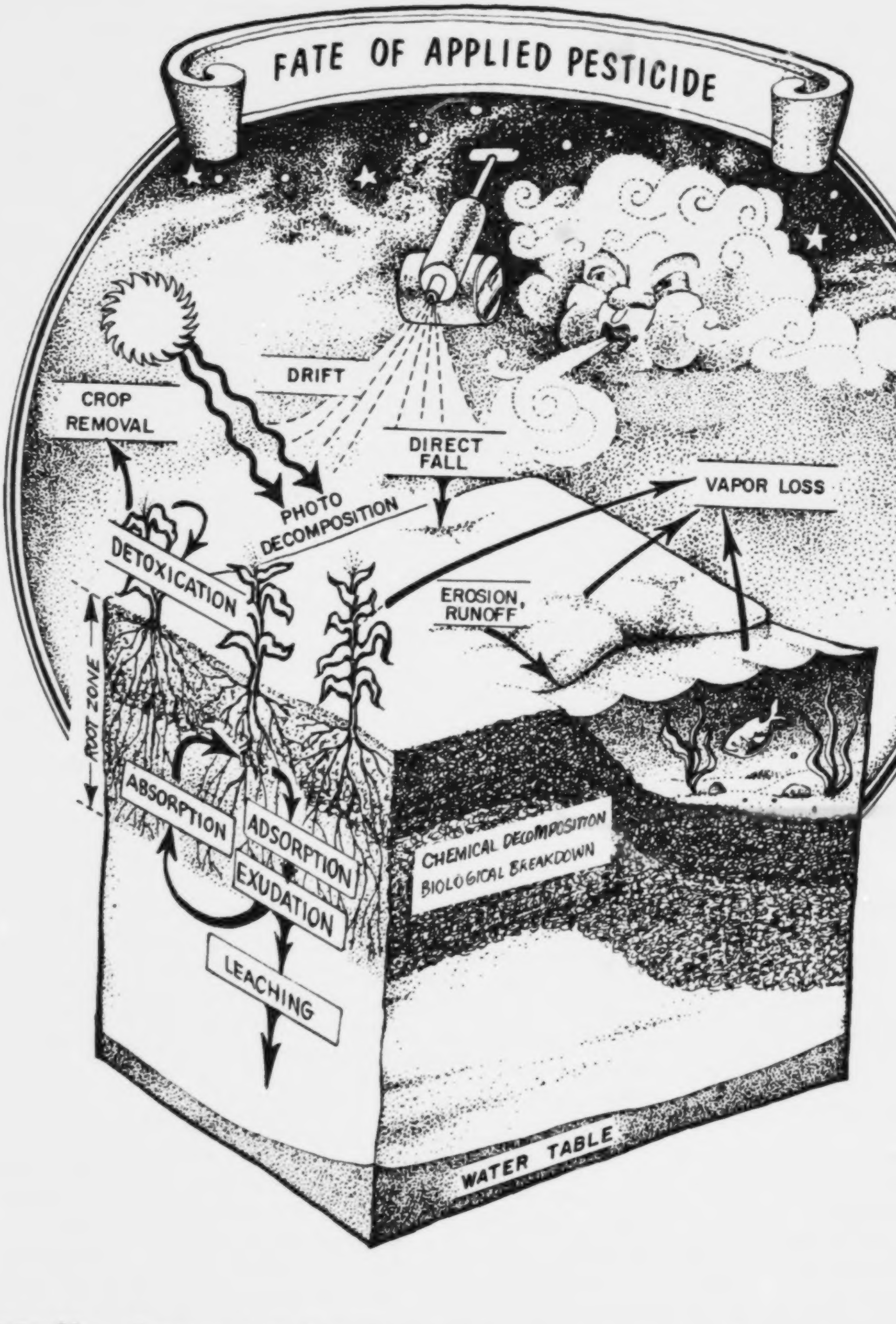
FATE OF APPLIED PESTICIDE
DRIFT
CROP REMOVAL
DIRECT FALL
PHOTO DECOMPOSITION
VAPOR LOSS
DETOXICATION
EROSION, RUNOFF
ROOT ZONE
ABSORPTION
ADSORPTION
EXUDATION
CHEMICAL DECOMPOSITION
BIOLOGICAL BREAKDOWN
LEACHING
WATER TABLE

Figure 22. Processes influencing the fate and behavior of pesticides.

concentration in runoff water and sediment. Infiltrating water will carry some of the pesticide into the soil before surface runoff begins, resulting in a lower concentration in the runoff water.

Chemicals which are weakly adsorbed will move with deep percolation water; those which are strongly adsorbed move mainly with sediments; and those with intermediate adsorptivity will move with both water and sediment. Even though the pesticide concentration may be higher in the sediment than in runoff water, as is often the case (see Table 32), the total amount of pesticide in the water may be greater because the amount of runoff water is usually much greater than sediment loss.

TABLE 32. CONCENTRATIONS OF PESTICIDE RESIDUES IN TAILWATER PITS SERVING CORN AND SORGHUM FIELDS IN HASKELL COUNTY, KANSAS, AVERAGED OVER 2 YEARS [1]

Pesticide	Samples containing the pesticide		Mean concentration of the pesticide in positive samples	
	Sediment	Water	Sediment	Water
	- - - percent - - -		parts per billion	
Atrazine	26	38	76	41
Cyanazine	50	44	42	29
EPTC	64	67	41	1
Fonofos	27	47	90	1
Parathion	0	100	0	2
Phorate	67	82	47	1

[1] Kadoum and Mock, 1978.

Most pesticide losses occur in the first runoff event following application, and the sooner this happens, the greater the losses. The same is true on sandy soil where percolation can occur. Pesticide adsorption and degradation in the soil reduces the amount of pesticide available for water transport.

Pesticides in Runoff Water--

Runoff losses of pesticides from an individual field are vastly different than from a large watershed because of the attenuation processes between the field and water course; therefore, generalizations of the amounts of pesticides lost to the edge of a field are presented in this section. These generalizations are a summary of Wauchope's review (Wauchope, 1978).

Wettable powder pesticides (all are herbicides applied to the soil) show the highest long-term losses. Losses up to 5 percent can be expected from slopes of 10-15 percent and losses up to 2 percent from slopes of 3 percent or less. If a large runoff event occurs within two weeks after a pesticide application, losses may be three times larger. Emulsions of water-insoluble pesticides show long-term losses of 1 percent or less. Water soluble pesticides incorporated into the soil show seasonal losses of 0.5 percent or less. As with wettable powders, initial losses can increase three-fold with large water runoff events.

Pesticide concentration also varies during the irrigation season, depending on the timing of irrigation relative to the pesticide application, as illustrated in Table 33. Herbicides, which are mostly applied during planting or shortly after crop emergence, had the greatest concentrations in both sediment and water during June in this study.

TABLE 33. DISTRIBUTION OF PESTICIDE RESIDUES OCCURRING IN TAILWATER PITS DURING IRRIGATION SEASON [1]

	Concentration in sediment				Concentration in water			
Pesticide	May	June	July	Aug.	May	June	July	Aug.
	- - - parts per billion - - -				- - - parts per billion - - -			
Herbicides:								
Alachlor	0	47	30	0	38	9	0	0
Atrazine	38	124	65	32	47	87	19	7
Cyanazine	0	32	21	2	18	30	21	1
EPTC	4	26	8	0	0	2	0	0
Propazine	43	90	81	20	25	60	24	5
Terbutryn	0	117	36	34	0	12	3	2
Insecticides:								
Carbofuran	0	5	7	0	6	3	1	0
Disulfoton	0	0	0	36	0	0	0	0
Fonofos	9	305	101	14	0	2	0	0

[1] Modified from Kadoum and Mock, 1978.

Only limited data are available on the impairment of water quality of surface or groundwaters by pesticides. Attenuation processes which occur as the pesticides are transported from the site of application to the receiving stream decrease pesticide concentrations and amounts. Levels of pesticides, when detected, are in the parts per billion (ppb) range or lower.

Wauchope (1978) made rudimentary estimates of pesticide runoff losses. Pesticides were placed in three groups and "rules-of-thumb" were proposed for predicting annual losses that can be useful in evaluating potential water quality problems for large agricultural areas. These estimates are:

(1) Foliar-applied Organochlorine Insecticides--Although persistent, these have largely been replaced by other insecticides and are not widely used on cropland in the Great Plains. Toxaphene is the only one listed in Table 30. An average of 1 percent per year of the amounts applied can be used for estimating runoff losses.

(2) Wettable Powder Formulations--Wettable powder herbicides, although not all persistent, have consistently high losses and are widely used in the Great Plains. Dissipation and dilution processes probably occur after these herbicides leave the field because they are seldom detected in receiving waters. However, loss estimates of 2 percent for 10 percent slopes or less, and 5 percent for areas of over 10 percent slopes were suggested for these materials.

(3) Nonorganochlorine Insecticides, Incorporated Pesticides, and All Other Herbicides--All remaining pesticides belong in this group which contains 61 percent of the herbicides and 98 percent of the insecticides from Tables 29 and 30. Many of them are water soluble, are not strongly adsorbed to soil sediments, and have short persistence. Although variable, one-half percent loss for these pesticides has been suggested as reasonable.

The amount of pesticides delivered to water sources was estimated in the Iowa Areawide Wastewater Management Study (Harmon and Duncan, 1978). The expected values, based on adsorption classes, are given in Table 34. Attenuation processes between the edge of the field and surface waters were not considered. It was suggested that these estimated values are probably high in view of the actual amounts of pesticides normally found in surface waters. These values basically agree with the percentages suggested by Wauchope (1978).

TABLE 34. ESTIMATED PERCENTAGES OF APPLIED PESTICIDES DELIVERED TO SURFACE WATER SOURCES [1]

Adsorption class [2]	Estimated losses of applied pesticides: In water, Normal range	In water, Maximum [3]	In sediment, Normal range	In sediment, Maximum [3]
	- - - percent - - -		- - - percent - - -	
Weak	0-1	10	0-0.1	1
Medium	0-5	20	0-1	4
Strong	0-0.5	2	0-2	10

[1] Harmon and Duncan, 1978.

[2] Weak: weakly held by soil colloids, readily leached in sandy soils low in organic matter (1 percent or less), some movement in other soils.

Medium: moderate attraction by soil colloids, moderate movement in sandy soils low in organic matter but little or no movement in other soils.

Strong: strongly held by soil colloids, slight leaching in sandy soils low in organic matter but little or no movement in other soils.

[3] Numbers are estimates of maximum pesticide losses that could be expected under very unusual pesticide-soil-water conditions.

The distance between the treated agricultural site and final water course is an important factor influencing the amount of pesticide entering that course. For example, runoff losses from a 6 hectare watershed for the herbicides alachlor, propachlor, and cyanazine were 0.54, 0.26, and 1.05 percent of the amounts applied. However, of the total applied within the 5,055 hectare watershed, runoff losses of these same herbicides were only 0.10, 0.14, and 0.08 percent, respectively, equaling 17 percent of the edge-of-field losses (Harmon and Duncan, 1978). During a five-year study in Nebraska, pesticides were found in 14 percent of the water samples (Table 35). One herbicide (2,4-D) was found at all seven locations. Concentrations of the pesticides were usually less than 1 ppb.

TABLE 35. SUMMARY OF PESTICIDES FOUND IN WATER IN NEBRASKA (1971-1976) [1/]

Stream location	Number of measurements (approx.)	Number of positive measurements	Pesticides normally found
Platte River at North Bend	260	11	2,4-D Diazinon
Logan Creek at Pender	90	18	Aldrin DDE DDT Dieldrin 2,4-D
Elkhorn River at Waterloo	400	37	Dieldrin Diazinon 2,4-D 2,4,5-T
Salt Creek above Beal Slough	340	29	2,4-D 2,4,5-T
Salt Creek below Stevens Creek	370	101	2,4-D Diazinon Lindane 2,4,5-T Silvex Dieldrin
Big Blue River near Crete	280	53	2,4-D 2,4,5-T Diazinon Dieldrin
Little Blue River at Hollenberg	270	34	2,4-D 2,4,5-T

[1/] U.S. Geological Survey, 1971-1976.

Groundwater from irrigation wells in corn-growing areas of Merrick County, Nebraska (Subarea 1021, as discussed in Section 1), where NO_3-N concentrations exceed 5 ppm were analyzed for atrazine (Spalding, et al., 1979). The NO_3-N and atrazine concentrations of the 18 samples are shown in Table 36. The lowest concentrations were found beneath poorly-drained (fine-textured) soils where less leaching, more adsorption, and faster degradation are expected. Atrazine, although not a highly soluble pesticide, leached into the shallow groundwater under sandy soils because soil adsorption was low and water percolation was high, conditions which are highly conducive to mass flow. Atrazine has probably been applied annually in this area for 15 to 20 years at rates of 1 to 3 kg per hectare per year.

TABLE 36. ATRAZINE AND NITRATE-NITROGEN CONCENTRATIONS IN WATER FROM IRRIGATION WELLS IN MERRICK COUNTY, NEBRASKA [1]

Soil characteristics		Atrazine		NO_3-N	
Drainage	Surface-texture	Ave.	Max.	Ave.	Max.
		- - ppb - -		- - ppm - -	
Somewhat poor	Loam-clay loam (Fine-textured)	0.25	0.44	13	26
Moderate	Sandy loam-loam (Medium-textured)	1.44	3.99	24	30
Well	Fine sandy loam-loam (Coarse-textured)	1.52	6.96	20	31

[1] Modified from Spalding, et al., 1979.

The persistence of atrazine, especially in sandy soils, enhances its opportunity for leaching.

The Water Quality Report for the International Garrison Diversion Study Board (Int. Garrison Diversion Study Board, 1976) indicated that the probability of pesticides in runoff from irrigated lands was very low during the growing season in North Dakota. Herbicides rarely were found in the irrigated regions of the Souris River despite widespread use of pesticides. However, it was conceded that pesticides could appear in IRF from direct surface runoff in the springtime (Bauder, per. com.).

Influence of Management Practices on Pesticide Losses--

Pesticide losses can best be controlled through a combination of runoff- and erosion-limiting devices. Erosion management alone will not provide a total solution because pesticide losses are usually greater in water runoff than in sediment.

Most extensive pesticide losses occur when precipitation closely follows pesticide application, usually in the spring when pesticide application is at its peak and thunderstorms are prevalent (Wauchope, 1978). Total dosage applied is extremely important when applications are made during the rainy or irrigation season. Frequent applications of less persistent materials may cause more problems due to the higher probability of rainfall immediately following these applications. Careful attention to correct application rate, the substitution of alternative pesticides or control methods (particularly if conditions are conducive to runoff or leaching) or soil incorporation of the pesticide can decrease pesticide losses from runoff.

Other management practices for controlling pesticide losses have been suggested; however, their relationship to other crop production management practices is complex (Caro, 1976; Harmon and Duncan, 1978; Dean and Mulkey, 1978). Greater losses usually result when pesticides are used unnecessarily or in excessive amounts.

Improved soil-water management can reduce pesticide losses by reducing runoff. Reduced tillage systems, which leave more surface residue, reduce losses of chemicals transported in sediment, but may only have a minor impact on soluble chemical losses (Bondurant and Laflen, 1978; Harmon and Duncan, 1978).

Proper irrigation water management practices are effective in reducing the movement and accumulation of pesticides. Runoff is most likely to occur with the first irrigation after pesticide application, and if that irrigation closely follows application. The danger of pesticide movement is essentially eliminated if the irrigation is not sufficient to cause excessive surface water runoff. Catching the irrigation tailwater will reduce the likelihood of pesticide runoff entering a water course.

It is unlikely that potential pesticide losses can be eliminated on irrigated lands, especially in runoff from slopes exceeding 12-18 percent (Harmon and Duncan, 1978). On coarse-textured soils and at lower levels of irrigation management, the probability of movement with deep percolation increases.

SECTION 3

AVAILABLE ON-FARM IRRIGATION MANAGEMENT ALTERNATIVES FOR REDUCING POLLUTION FROM IRRIGATION RETURN FLOWS

by

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The specific water quality problems resulting from nonpoint source pollution from irrigation return flows were presented in the preceding section. Section three deals with the various alternative measures which can be taken to reduce or control pollution problems resulting from irrigation return flows. Direct water runoff and deep percolation from irrigated cropland resulting from applied irrigation water can rarely be eliminated. However, it can be reduced and, in some cases, substantially reduced by carefully-selected combinations of management practices. Specific practices directed to the control of irrigation return flows under each of five alternative management options are discussed. These alternative irrigation management options given in Table 37 are:

1. irrigation system management
2. on-farm water management
3. soil management
4. nutrient management
5. pesticide management.

It is important to recognize that these five management options are not totally independent. Interrelationships exist among them which may affect the choice of a particular practice in a given situation. Compromises may be necessary. The choices must meet not only environmental requirements but also meet the economic need of specific situations. For example, increasing the stream size and reducing water application time for furrow irrigation systems may decrease the amount of pollutants contributed by deep percolation, but may increase the amount of surface runoff. Thus, a reuse system must be installed to capture the runoff water to reduce pollution by surface return flows. Likewise, the introduction of conservation tillage to control erosion may result in the use of greater amounts of chemicals to control crop pests, so that the net benefit to the quality of the irrigation return flows may not be as great as might be expected. Some of the more important interrelationships are described in the discussions of individual management options. Some specific control practices are listed and discussed that are of marginal value in many cases. However, in a particular set of circumstances, one of these practices could be the best recommendation.

TABLE 37. ALTERNATIVE IRRIGATION MANAGEMENT OPTIONS TO REDUCE POLLUTION FROM IRRIGATION RETURN FLOWS

Management option	Table number in this section
1. Irrigation system management	
--Types of irrigation systems	38
--Potential pollution rating of surface and trickle systems	39
--Potential pollution rating of sprinkler systems	40
--Surface and trickle irrigation management	41
--Sprinkler irrigation management	42
2. On-farm water management	43
3. Soil management	44
4. Nutrient management	45
5. Pesticide management	46

The pollution reduction capability of specific control practices within each management option is estimated by comparing the specific practice to a particular standard. This rating scale is:

Low (L)	0-10 percent reduction
Moderate (M)	10-50 percent reduction
Substantial (S)	50-100 percent reduction.

It must be emphasized that these ratings are only estimates. Many of the ratings given in the tables are based on limited quantitative data. The judgment of the authors was used when no data existed. Furthermore, the singular impact of any control action individually applied to a given irrigation situation may be rated low. In contrast, when that same control action is used as one of several supporting practices in a control program, its impact may be higher than estimated. The impact of a given control practice will vary depending on the individual site.

IRRIGATION SYSTEM MANAGEMENT

The general types of irrigation systems evaluated herein are listed in Table 38. Descriptions of these systems were given in Section 2.

Evaluations of the potential pollution from surface and trickle irrigation systems and sprinkler irrigation systems as a function of soil type and slope are shown in Tables 39 and 40, respectively. These ratings

TABLE 38. IRRIGATION SYSTEMS DISCUSSED UNDER THE ALTERNATIVE MANAGEMENT OPTIONS

Irrigation system [1/]
SURFACE:
Contour Ditch (Wild Flooding)
Graded Borders
Furrows without reuse system
Open ditch
Siphon tube
Gated pipe
Furrows with reuse system
Open ditch
Siphon tube
Gated pipe
Automated gated pipe with reuse system
SPRINKLER:
Solid Set
Center-Pivot [2/]
Moved (hand move, side-roll, skid-tow)
Moving (travelers, boom)
TRICKLE:
Trickle/Drip

[1/] The individual systems are described in greater detail in Section 2.

[2/] Including low pressure center-pivot systems.

TABLE 39. POTENTIAL POLLUTION RATING OF SURFACE AND TRICKLE IRRIGATION SYSTEMS [1]

Types of surface and trickle irrigation systems [2]	Coarse-textured soil [3] (Sand to loamy sand)				Medium-textured soil [4] (Loam to silt loam)				Fine-textured soil [5] (Silty clay to clay)			
	Land slope (percent)				Land slope (percent)				Land slope (percent)			
	0-2	2-4	4-6	>6	0-2	2-4	4-6	>6	0-2	2-4	4-6	>6
SURFACE:												
Contour ditch	H	H	H	H	M	H	H	H	M	H	H	H
Graded borders	H	H	H	H	M	H	H	H	L	M	M	M
Furrows without reuse	H	H	H	H	M	H	H	H	M	H	H	H
Furrows with reuse	M	H	H	H	L	M	M	M	L	L	M	M
Automated gated pipe with reuse	M	M	M	H	L	L	L	M	L	L	L	M
TRICKLE:												
Trickle/Drip	L	L	L	L	L	L	L	L	L	L	L	L

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[1] Rating Scale (Relative):

H - High potential pollution hazard
M - Moderate potential pollution hazard
L - Low potential pollution hazard

[2] Irrigation systems described more fully in Table 38.

[3] Primarily deep percolation problems.

[4] Both deep percolation and surface water runoff problems.

[5] Primarily surface water runoff problems.

TABLE 40. POTENTIAL POLLUTION RATING OF SPRINKLER IRRIGATION SYSTEMS [1]

Types of Sprinkler irrigation systems [2]	Coarse-textured soil (Sand to loamy sand) Land slope (percent)					Medium-textured soil (Loam to silt loam) Land slope (percent)					Fine-textured soil (Silty clay to clay) Land slope (percent)				
	0-2	2-4	4-6	6-10	>10	0-2	2-4	4-6	6-10	>10	0-2	2-4	4-6	6-10	>10
SPRINKLER:															
Solid Set	L	L	L	M	M	L	L	L	M	M	L	L	L	L	M
Center-Pivot [3]	L	L	L	M	M	L	L	M	H	H	M	M	H	H	H
Moved [4]	M	M	M	H	H	L	L	M	H	H	L	L	M	H	H
Moving [5]	L	L	M	H	H	L	L	M	H	H	M	M	H	H	H

[1] Rating Scale (Relative):

H - High potential pollution hazard
M - Moderate potential pollution hazard
L - Low potential pollution hazard

[2] Irrigation systems described more fully in Table 38.

[3] On fine-textured soils, primarily surface water runoff problems.

[4] On coarse-textured soils, primarily deep percolation problems.

[5] On fine-textured soils, primarily surface water runoff problems.

assume good (reasonable attainable) irrigation management. They are only general estimates indicating how pollution problems will increase or decrease depending on soil type and increasing land slope. The specific pollution problem on irrigated lands will have to be evaluated on an individual site basis.

Regardless of the degree of management, soil type, or irrigation system, steeper slopes increase the potential for pollution problems. Generally, slopes greater than 2 percent are not recommended for most surface irrigation systems, particularly on coarse-textured soils. Sprinkler systems can be used on steeper land slopes; however, they are not generally recommended for slopes over 6 percent on medium- and fine-textured soils because of the increased potential for runoff.

Even if properly selected and designed, a particular type of irrigation system is not always more efficient than another method. Changing from one irrigation system to another only constitutes a change in the method of water application. Such a change should not be made based on the premise that one system is always more efficient than another. Replacing a surface irrigation system with a sprinkler irrigation system can reduce pollution hazards in some situations. However, pollution hazards are dependent on both the type of system in use for the given soil type and the individual irrigator's management skills. A well-managed surface irrigation system may have less pollution problems than a mismanaged sprinkler system. We emphasize that the ratings of Tables 39 and 40 are only guides which have been developed to help the users of the manual better understand the response of irrigation systems under a given set of conditions.

The evaluation of irrigation systems depends on a number of variables considered for particular conditions. There are many situations where conversion from one irrigation system to another would not be feasible due to soils, topography, acreage, crop, economics, or energy requirements.

Surface Systems

The primary pollution hazards from surface irrigation systems are deep percolation losses from coarse-textured soils and the surface runoff on fine-textured soils. Medium-textured soils can be troubled with either problem, depending on water intake characteristics. The principal irrigation system management practices for controlling these losses are given in Table 41.

Proper operation of most surface irrigation systems (except for graded borders and level basins) requires water runoff to insure a uniform application of water. Tailwater reuse systems can be installed to capture both sediment and water runoff when maximum water stream sizes are used. Reuse of tailwater return flows can result in the removal of 40 to 70 percent of the sediment from the water runoff and can, in some cases, increase the irrigation efficiency by 30 percent. Other sediment retention systems can be used either separately or in conjunction with reuse systems to remove much of the sediment and considerably reduce pollution problems. Where

TABLE 41. IRRIGATION SYSTEM MANAGEMENT PRACTICES FOR SURFACE AND TRICKLE IRRIGATION SYSTEMS AND THEIR RELATED POLLUTION REDUCTION 1/ 2/

Specific control practice	Applicable irrigation system						Coarse-textured soil 3/ (Sand to loamy sand)		Medium-textured soil (Loam to silt loam)		Fine-textured soil (Silty clay to clay)	
	Contour ditch	Graded borders	Furrows w/o reuse	Furrows w/reuse	Gated pipe	Trickle	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff
Install tailwater reuse system	X	X	X				L	M	M	S	M	S
Land smoothing or leveling to control slope and shape	X	X	X	X	X		L	L	M	M	M	M
Match system to soil type and slope (Table 39)	X	X	X	X	X		L	L	M-S	M-S	M-S	M-S
Proper stream size (maximum nonerosive stream) with reuse system	X	X	X	X	X		M	L	M-S	L	M	L
Reduce length of run with reuse system	X	X	X	X	X		M-S	L-M	M-S	S	M	S
Use of cutback stream size without reuse system		X	X				L	L	L	L-M	L	L-M
Use of alternate furrow irrigation			X	X	X		L-M	L	L-M	L	L	L
Increased use of automated devices	X	X	X	X	X	X	L-M	L-M	L-M	L-M	L-M	L-M
Decreased set time with reuse system			X	X	X		M	L	M	L	M	L
Lining canals 4/	X	X	X	X	X		M-S	L	L-M	L	L	L
Replace system with sprinkler system	X	X	X	X	X		M-S	L	L	L	L	L

1/ Carter, 1976; Interagency Task Force, 1978; Kruse and Heermann, 1977; Merriam, 1977; Stegman, et al., in prep.; Westesen, 1977.

2/ Ranges in percent reduction compared to an existing system without the specific control practice: low (L) 0-10 percent, moderate (M) 10-50 percent, substantial (S) 50-100 percent.

3/ Surface irrigation systems on coarse-textured soils should be carefully designed and operated because of the potential deep percolation problems (Table 39).

4/ The benefits of canal lining depend greatly on local soil conditions. The area affected by canals is usually much smaller than the irrigated land, thus the benefit of canal lining is usually small.

surface irrigation systems are used on land which has been leveled, smoothed, or shaped, surface water runoff and soil loss are usually reduced. Where surface systems are correctly designed for soil type and slope (Table 39), deep percolation water losses will also be minimized if proper scheduling of irrigation and proper stream sizes are used.

Surface system designs are best improved by adjusting slope, altering the length of run (where field shape permits), and changing furrow stream sizes to obtain proper advance and recession of the irrigation stream. Stream sizes can be adjusted to advance water across the field in the fastest time possible. They must not, however, exceed the maximum nonerosive stream size if soil erosion is to be prevented.

Maximum nonerosive stream sizes and short set-times (a few hours) may be best used with automated surface irrigation systems to obtain the maximum irrigation efficiency. The maximum nonerosive stream size also can be used with manually operated gated-pipe or other nonautomated systems. However, the labor required for making frequent set changes using nonautomated systems makes this system impractical in most cases.

The addition of devices to measure and control water volumes within surface systems will considerably improve potential irrigation system efficiencies. Automation of water control in any irrigation system will increase the management capabilities of the system and, in turn, increase the efficiency of the system [Interagency Task Force, 1978, Kruse and Heermann, 1977; Fischbach (ed.), 1977].

Reducing the stream size of water flows after water reaches the end of the irrigated field and decreasing the length of water flow in the field also are practices that can control runoff and deep percolation losses. However, these practices require considerable labor and system equipment inputs. Irrigators may be reluctant to invest their management energies while other control practices are more readily available (Carter, 1976).

Sprinkler Systems

The primary pollution hazards from sprinkler irrigation systems are deep percolation losses caused by excessive water applications and surface runoff which may be caused by excessive water application rates. Practices for controlling these losses are given in Table 42.

Surface runoff of irrigation water usually will not occur with a properly designed sprinkler system that applies water no faster than the soil absorbs it. The automation of water application, at rates less than the soil infiltration rates, eliminates surface water runoff with subsequent reduction in sediment and nutrient losses. This automation is more easily adaptable with sprinkler systems than surface systems.

Sprinkler systems are adaptable to a wide range of land classes and soil types, and can be effectively used under varying conditions. However, it must be remembered that after a sprinkler irrigation system is designed

TABLE 42. IRRIGATION SYSTEM MANAGEMENT PRACTICES FOR SPRINKLER IRRIGATION SYSTEMS AND THEIR RATED POLLUTION REDUCTION 1/

Specific control practice	Coarse-textured soil (Sand to loamy sand)		Medium-textured soil (Loam to silt loam)		Fine-textured soil (Silty clay to clay)	
	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff
Design systems application rates as to not exceed soil intake rates 2/	L	L-M	L	L-M	L	M-S
Proper amounts of water applied per irrigation	L-M	L	L-M	L	L	L-M
Increase use of automated devices to control irrigation depths	L-M	L	L-M	L	L	L-M
Increase uniformity by improved design	L	L	L	L	L	L
Operate in periods of low wind velocities	L	L	L	L	L	L
Change design of system 2/	L-M	L	L	L-S	L	L-S

1/ Ranges in percent reduction compared to an existing system without the use of the control practice: low (L) 0-10 percent, moderate (M) 10-50 percent, substantial (S) 50-100 percent.

2/ Depends greatly on soil type and type of irrigation system. Extra caution should be used when low pressure center-pivots are placed on medium- and fine-textured soils, because of high application rates.

and installed, the irrigator's management ability ultimately determines the efficiency with which the system operates and the resulting pollution from the system. Individual types of systems must be assessed to evaluate their ability to reduce pollution problems (Stegman, et al., in prep.).

A change from surface to sprinkler irrigation is needed on soils having high infiltration rates that cause excessive deep percolation or where land slopes are uneven and steep (Table 39 and 40). Sprinkler irrigation systems are more easily controlled through adjustments to application frequency, depending on crop water-use requirements or soil moisture profile characteristics (Stegman, et al., in prep.; Westesen, 1977). Thus, conversion from surface to sprinkler irrigation may be suggested as a means of reducing irrigation return flow on coarse-textured soils, especially on sloping lands.

Trickle Systems

Less water can generally be applied with trickler/drip irrigation systems. Because only the plant root zone is supplied with water, little water is lost to deep percolation and none to surface water runoff. Trickle systems are amenable to customized crop-field designs, for sophisticated automation, and installation and placement on any soil type or slope of land. However, trickle/drip systems require excellent water filtration equipment and demand skilled technical labor and management.

Trickle/drip systems have the highest capital costs of all irrigation systems. Generally, only irrigation of specialty, high-value cash crops such as vegetables and fruit can be considered an economical use of this system. As with any irrigation system, economic considerations may limit applicability in a specific situation.

ON-FARM WATER MANAGEMENT

Current on-farm water management practices alone or in combination with other existing practices, such as nutrient and pesticide applications, may contribute to inefficient irrigation practices and increase pollution from irrigation return flows. Specific water management practices and their rated pollution reduction are given in Table 43. While proper water management practices under a given irrigation system are of utmost importance in reducing pollution, these practices are highly related to the other control practices discussed.

Irrigation Scheduling

Experience has shown that irrigators generally know when to apply water, but may not know how much to apply at a given time. By employing irrigation scheduling techniques (Jensen, et al., 1970), irrigators or competent consultants (Gilley, 1978) can determine the amount of water required to refill the crop root zone to meet crop water-use requirements. Several irrigation

TABLE 43. ON-FARM IRRIGATION WATER MANAGEMENT OPTIONS AND THEIR RATED POLLUTION REDUCTION 1/ 2/

Management option	Specific control practice	Coarse-textured soil (Sand to loamy sand)		Medium-textured soil (Loam to silt loam)		Fine-textured soil (Silty clay to clay)	
		Deep percolation	Surface water runoff	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff
Irrigation Scheduling	a. Adopt a water scheduling procedure	M-S	L-M	L-M	L-M	L-M	L-M
	b. Employ flow measuring services	M-S	L-M	L-M	L	L	L
	c. Increase use of automated devices to control irrigation timing and amounts	L-M	L	L	L	L	L-M
	d. Scheduling procedures allowing a soil moisture deficit to maximize rainfall 3/	L-M	L-M	L-M	L-M	L	L-M
	e. Alternate cropping practices to modify irrigation schedules	L	L	L	L	L	L-M
	f. Reduction in preplant irrigation	L-M	L	L-M	L	L	M
	g. Follow leaching 4/ recommendations for irrigation water quality and crop	L	L	L-M	L	L-M	L
Adjust Crop Water Demands	a. Modify selection of crop type and variety	L	L	L	L	L	L
	b. Use crops which use less water	L	L	L	L	L	L
	c. Reduce irrigation amounts below crop needs 5/	M	L	L	L	L	L

1/ Fischbach (ed.), 1977; Fitzsimmons, et al., 1978; Interagency Task Force, 1978; Jensen, 1975; Merriam, 1968, 1977; Walker, et al., 1978.

2/ Ranges in percent reduction compared to existing practices: low (L) 0-10 percent, moderate (M) 10-50 percent, substantial (S) 50-100 percent.

3/ This procedure should be used with caution on coarse-textured soils with low water-holding capacities.

4/ Some deep percolation is necessary to remove the salts from the root zone so that the cropland remains productive.

5/ Severe yield reductions may result from this practice.

techniques can be adopted. These include: (1) soil measurements; (2) computed water balance; or (3) evaporation devices (Jensen, 1975; Stegman, et al., in prep.). In some areas, irrigation scheduling may provide for a soil-moisture deficit in the program to make the maximum use of rainfall. Of course, this procedure should not be used in either low rainfall areas or in areas of predominantly coarse-textured soils which have minimal soil-moisture holding capacity.

Irrigation scheduling is necessary, but is only one method for improved water management. Scheduling must be incorporated with other on-farm irrigation management practices to achieve maximum irrigation water management. Management has become so sophisticated that computers are used in processing of scheduling data. In some cases, computer simulation tests are used to determine the interactions of the various soil types, crop types, rainfall characteristics, and irrigation system combinations for customized scheduling problems.

The recognized value of carefully controlling the amounts and timing of water applications usually justifies the increased equipment needs of a control system. A water meter, for example, can be a valuable tool in the proper application and scheduling of irrigation water. Most devices can be automated, dependent on the degree of control required for a specific irrigation system. The switch to automatic water measuring meters increases capital outlays, but should reduce energy demand and management costs over time.

Crops have different demands for water and times of peak water-use needs. The modification of irrigation practices during the early part of the irrigation season can limit pollution from irrigation exceeding the crop use demands. For example, a light application of irrigation water early in the crop season, when the water requirement and nutrient uptake are low, will result in reduced nutrient leaching, as compared to a large application of irrigation water.

Irrigation system operation can be changed to more closely match the soil intake rates and crop water demands throughout the season. These changes must be flexible enough to meet peak water demands, but the system should be operated to this capacity only during peak water demand periods. System changes should therefore consider the rate of crop water use during the entire irrigation season. The ability of the irrigation system to reduce pollution will depend on the ability of the system to supply limited amounts of water when crop needs are low.

In some irrigated areas, on-farm water management decisions must consider the quality of water used for irrigation. Irrigation waters contain salts in varying concentrations. The water's suitability for irrigation use is determined both by the kinds and amounts of salts in the water. Poor water quality may cause reduced crop yields. Deep percolation or drainage water reflects not only the application water quality but also the salt content of the land. Different scheduling and water management system practices can be selected to create favorable salt balances within the spectrum of water qualities used for irrigation [Ayers and Westcot, 1976; Fischbach, (ed.) 1977; and Walker, 1977]. Decisions about leaching/drainage control practices will then depend on the amount of water applied.

Adjust Crop Water Demands

A reduction in crop water demands during the growing season or a shift of the demand from one time during the growing season to another can reduce or modify the water application amounts. These changes also may reduce deep percolation losses. Crop water demands during the irrigation season might be modified by: (1) selection of different crop species (using a multiseason crop mix, using double cropping or altering growing periods by changing planting dates); (2) using crops which require less water; and (3) reducing the irrigation amounts below crop water needs or stressing crops to reduce water demands. These procedures most likely are limited to very specific situations. Their imposition would be limited by agronomic considerations and by economics. Clearly, if these procedures were simple to implement, and, in general, economically rewarding, they would have already been widely adapted. They have been presented here only because factors other than irrigation return flows may force the use of some of these procedures at some locations.

SOIL MANAGEMENT

The rated pollution reduction of specific soil management practices for controlling surface water runoff and deep percolation losses from irrigation return flows is given in Table 44. These practices are primarily beneficial in the reduction of surface water runoff and the associated reduction in sediments, nutrients, and pesticides in this runoff. Because soil moves with water, controlling water runoff will also control soil erosion and the resulting sedimentation. Soil management practices can be combined with other irrigation management practices best suited to local conditions.

Many of the practices given in Table 44 are discussed in the November 1975 U.S.D.A./E.P.A. publication "Control of Water Pollution from Cropland - Vol. 1," by B. A. Stewart, et al., which judges the effectiveness of specific practices used to control runoff and erosion from rainfall. These practices have similar benefits in controlling runoff and erosion from irrigation water. Some of the practices given in Table 44 will not be practical under all types of irrigation systems. Their use in an overall irrigation management program must be evaluated on an individual basis.

Carefully designed and managed sprinkler irrigation systems create little or no surface runoff of irrigation water. The runoff that does occur, especially during early season irrigations, can be safely disposed of with a grassed waterway or outlet, which prevents excessive soil loss and the formation of gullies. Vegetative residues left over from the winter protect soils during critical periods of early erosive irrigations and rains. Vegetative sediment filters, settling basins, and sediment traps represent practices for sediment reduction. While they are not erosion control

TABLE 44. SOIL MANAGEMENT OPTIONS FOR CONTROLLING IRRIGATION RETURN FLOWS AND THEIR RATED POLLUTION REDUCTION 1/ 2/

Management option	Specific control practice	Coarse-textured soil (Sand to loamy sand)		Medium-textured soil (Loam to silt loam)		Fine-textured soil (Silty clay to clay)	
		Deep percolation	Surface water runoff	Deep percolation	Surface water runoff	Deep percolation	Surface water runoff
Land Modification	Land smoothing or leveling	L	L	M	M	M	M
	Terraces 3/	L	L	L-M	L-M	L	M-S
	Sediment basin 4/	L	L	L	M-S	L	M-S
	Grassed waterway or outlet	L	L	L	L-M	L	L-M
Cultural Practices	Permanent vegetation 5/	L	L	L	L-M	L	L-M
	Sod-based rotation 6/	L	L	L	L-M	L	L-M
	Meadowless rotation	L	L	L	L	L	L
	Conservation tillage 7/	L	L	L	L-M	L	L-M
	Improved soil fertility 8/	L-S	L-S	L-S	L-S	L-S	L-S
	Timing of operation	L	L	L	L	L	L
Supporting Practices	Contouring 9/	L	L	L	L-M	L	L-M
	Contour strip cropping 10/	L	L	L	L-M	L	L-M
	Vegetative strips 11/	L	L	L	L-M	L	L-M
	Diversions	L	L	L	L	L	L
	Drainage	L	L	L	L	L	L

1/ Carter and Bondurant, 1976; Fitzsimmons, et al., 1977 and 1978; Stewart, B. A., et al., 1975 and 1976; Walter, et al., 1977.

2/ Ranges in reduction compared to continuous row cropping, conventionally tilled, up and down slopes, used as a basis for comparison: low (L) 0-10 percent, moderate (M) 10-50 percent, substantial (S) 50-100 percent. The effectiveness of any practices is relative to total amounts of nutrient rather than concentrations of these materials.

3/ The use of terraces under some irrigation systems may not be practical. By reducing surface water runoff, deep percolation losses may be increased.

4/ Applies primarily to surface systems.

5/ Degree of control is dependent on type of vegetation and amount of ground cover. Reduction of cash crop acreage will reduce income.

6/ Reduction of cash crop acreage will reduce income.

7/ Some types of conservation tillage practices under surface irrigation systems may result in poor water application uniformity and may increase deep percolation losses. Their relative effectiveness is related to the amount of residue left on the surface and the amount of surface storage created by the tillage operation.

8/ Depending upon the fertility level of the standard for comparison, low to substantial effects have been reported.

9/ The use of this practice may not be practical under some types of irrigation systems.

10/ The use of this practice may not be practical under some types of irrigation systems. Reduction of cash crop acreage will reduce income.

11/ Primarily at lower end of surface irrigation systems.

practices, they can be effectively used to trap sediments near their source.

An improvement in soil structure usually increases water intake rates. However, only a few control practices such as reduced tillage result in soil structure improvements. These improvements may reduce runoff by allowing more surface water to enter the soil profile. Conservation tillage systems can be suited to a broad range of soil and climatic conditions, with good options for fertilizer placement. Under many conditions, crop yields are as good as, and sometimes higher than those obtained with the plow-based system. Some of the practices require equipment modification, but human and machine hours and soil compaction by implements are usually reduced.

The effectiveness of a particular system or machine depends on how the soil surface is affected. The effectiveness is directly related to the amount of residues left on the surface, the amount of residues mixed into the upper few inches of topsoil, surface roughness, and ridges or residue strips on the contour. Only fragmentary data are available to quantify the runoff reduction that might be achieved by each practice. When used without support practices, runoff will be slightly to moderately reduced. Runoff may be reduced substantially if reduced tillage is used in conjunction with contouring.

Rotating two row crops, or a row crop and a small grain, does not provide the erosion control of a sod-based system. However, such rotations help control some diseases and pests and can reduce the amount of pesticides required. Direct runoff may be slightly reduced in the years the field is in small grain, but it apparently has no residual effect on infiltration capacity in the row-crop year. Rotations involving only row crops (corn and soybeans, for example) would have approximately the same direct runoff potential as continuous corn. However, given the present price structure, there may be serious economic drawbacks to the use of certain crop rotations and cover crops.

Change in land use is sometimes the only solution. Properly managed hay or pasture furnishes adequate erosion control over a wide range of slopes. Sometimes, a change to annual cropping of small grains and other closely seeded crops, with appropriate tillage practices and residue management, will suffice. Obviously, substantial local changes in land use will often have serious adverse economic effects on the farmer and the region.

NUTRIENT MANAGEMENT

The loss of soil nutrients was occurring long before lands were plowed, farmed or irrigated. Modern farming and irrigation practices have only accelerated these nutrient losses. Nutrient losses cannot be eliminated, but they can be reduced by the implementation of management practices and application of technical information available today. A number of practices will reduce surface runoff, soil erosion, or both and thus control overland surface nutrient transport. In some cases, such as leaching of nutrients by deep percolation, alternative practices must be used to reduce losses of soluble nutrients.

Nitrogen and phosphorus are the nutrients most commonly required by crops, applied to the soil, and lost through present agricultural practices. Where high rates of chemical fertilizer are applied to supplement the nutrients present in the soil, the potential for pollution will usually be highest.

Sufficient soil fertility research data are available to provide guidelines for the plant nutrients needed for optimum crop production. Thus, the problem of applying excessive amounts of nutrients such as nitrogen and phosphorus is not one of being able to predict the amount needed but rather one of recognizing the environmental pollution caused by over-application. It is fundamental to pollution control that fertilizers should not be added unless they are needed. It is assumed that this first step of accurately matching the rate of application of N and P nutrients to the needs of a given crop has already been taken; that a realistic yield goal consistent with the crop production capability of the soil and climate conditions has been determined; and that proper management adjustments of recommended fertilizer application have been provided.

Concentration of nutrients in the soil alone is not a good indicator of potential losses. Nutrient concentration reflects both the amount and timing of applications based upon the plant demands for the type of nutrient applied. Both amount and timing strongly affect the efficient use of nutrients by plants. The least possible nutrient loss will occur when fertilizer is applied as close as possible to the time of use by the crop. The management of nutrient application methods in relation to plant root distribution and soil moisture is important in increasing the effective use of fertilizers. Excessive application, along with improper timing and/or improper method of fertilizer application contributes to nutrient losses through direct runoff and deep percolation. (Stewart, B. A., et al., 1975, 1976; Harmon and Duncan, 1978).

A list of management alternatives for optimum nutrient application is given in Table 45. The effectiveness of these management practices was estimated for limiting nutrient losses from either surface or sprinkler irrigation methods.

Mobile Nutrients Under Surface Irrigation

The application of nutrients in irrigation water, a practice referred to earlier as fertigation, is becoming more extensive. Through careful timing, the supply of mobile nutrients can more closely match the peak crop demand. However, the proper management of irrigation and nitrogen application is necessary even if the nitrogen is applied with the irrigation water.

TABLE 45. MANAGEMENT ALTERNATIVES FOR OPTIMUM (NOT EXCESSIVE) NUTRIENT APPLICATION[1]

Nutrient application method [2]	Coarse-textured soil (Sands to loamy sands) [3]				Medium-textured soil (Loams to silty loams) [3]				Fine-textured soil (Silty clays to clays) [3]			
	Deep percolation		Surface runoff		Deep percolation		Surface runoff		Deep percolation		Surface runoff	
	Most mobile	Least mobile	Most mobile	Least mobile	Most mobile	Least mobile	Most mobile	Least mobile	Most mobile	Least mobile	Most mobile	Least mobile
SURFACE												
Increment as needed (Fertigation)	S	NA [4]	[5][6]	NA [4]	S	NA [4]	[5][6]	NA [4]	S	NA [4]	[5][6]	NA [4]
Split (Preplant & side-dress)	M	NA	↓	NA	M	NA	↓	NA	M-S [7]	NA	↓	NA
Side-dress only	S	NA	↓	NA	M-S [7]	NA	↓	NA	S	NA	↓	NA
Preplant (Spring)	L-M [10]	NA	↓	NA	L-M [7]	NA	↓	NA	M	NA	↓	NA
Fall applied	L	NA	[8]	NA	L	NA	[8]	NA	L	NA	[8]	NA
SPRINKLER												
Increment as needed (Fertigation)	S	NA	[6]	NA	S [7]	NA	[6]	NA	S [7]	NA	[6]	NA
Split (Preplant & side-dress)	M	NA	↓	NA	[9]	NA	↓	NA	[9]	NA	↓	NA
Side-dress only	S	NA	↓	NA	S [7]	NA	↓	NA	S [7]	NA	↓	NA
Preplant (Spring)	L-M [10]	NA	↓	NA	M	NA	↓	NA	M-S [7]	NA	↓	NA
Fall applied	L	NA	[8]	NA	L	NA	[8]	NA	M	NA	[8]	NA

[1] Frere, 1976; Fried, et al., 1976; Horner, et al., 1978; McNeal and Pratt, 1978; Stewart, B. A., et al., 1975 & 1976; Harmon and Duncan, 1978.

[2] The potential for leaching losses decreases for all the nutrient application practices as the soil becomes finer-textured.

[3] Ranges in percent reduction of nutrient losses compared to existing methods without the specific management method for nutrient application: low (L) 0-10 percent, moderate (M) 10-50 percent, substantial (S) 50-100 percent. Comparison of the relative efficiency of various practices are made only within soil textural classes and not across soil classes. For example, an (S) rating for a practice on sandy soil may connote a greater overall reduction of potential than an (S) rating on the finer-textured soils.

[4] NA indicates these particular fertilizer management practices have no influence on irrigation-related pollution problems.

[5] Incorporation of fertilizer will result in a moderate reduction in nutrient losses by runoff and erosion but would have little or no effect upon leaching.

[6] The only surface runoff losses of major consequence will occur with the most mobile nutrients with fertigation management practices; in surface irrigation when no tailwater reuse system is employed or with sprinkler application rates which exceed water intakes, and surface water runoff occurs.

[7] Rating depends a great deal on soil intake rate. A well-structured soil with a higher water intake rate will have a higher impact by this practice.

[8] Winter application of fertilizer on frozen ground may increase loss of nutrients because of surface water runoff.

[9] There is no need for a split application on these soils with proper water management practices.

[10] This rating depends on the N form and amount of spring rain. If the early season rainfall is less than 15 cm, both ammonium nitrate and ammonia fertilizers would have a rating of M. However, if the spring rainfall is less than 15 cm, ammonium nitrate fertilizer only would be rated L (Watts, et al., 1978).

Nitrates and other mobile ions are easily leached with excessive water applications. Without exception, however, the potential losses of mobile nutrients are the highest within the coarse-textured soils. Both the amount of fertilizer applied and the amount and timing of irrigation water must be controlled to limit leaching and thus, deep percolation pollution on coarse-textured soils. When nutrients are applied with irrigation water on medium- or fine-textured soils, a reuse system should be used to reduce the amount of runoff contributed to surface return flows. Soil incorporation of nitrogen fertilizers can moderately reduce nutrient losses caused by erosion or runoff but has little or no effect on deep percolation.

Split application, the application of part of the nitrogen in spring and the rest as summer side dressing, combines some of the timing features of each of the other methods of application. Fertilizer applications in the fall may be acceptable if leaching or surface runoff is not a problem. Coarse-textured soils are the exception. Residual nitrate or preplant nitrogen fertilizers may result in excessive losses of N if heavy spring rains occur, making them unavailable for the next season's crop. The problem of leaching residual nitrates is not as serious for irrigators on fine-textured soils because much more of the residual N generally remains in the root zone. However, some leaching losses do occur on well-structured soils.

Relatively Immobile Nutrients Under Surface Irrigation

The less mobile nutrients (phosphorus and calcium) generally are not applied during the irrigation season. Although management of these nutrients also reflects quantity, timing and placement of nutrient application, these practices have almost no effect on either deep percolation or runoff of these relatively immobile nutrients. Application practices likewise have little influence on losses because these nutrients are incorporated into the upper root zone where they remain. Losses of these nutrients are primarily related to sediment losses in surface runoff water and are determined almost entirely by the factors that influence sediment losses. Specific actions which reduce water runoff and erosion during the irrigation cycle will also reduce pollution from preplant and fall-applied less mobile nutrients. Where surface irrigation is used on erodible slopes and medium-textured soils, phosphate losses can be expected.

Mobile Nutrients Under Sprinkler Irrigation

As shown in Table 45, the estimated reduction in mobile nutrient losses with sprinkler irrigation is generally the same as the estimated reduction under surface irrigation. The amount and timing of both water and fertilizer applications can be adjusted with sprinkler systems to meet the needs of the growing crop. Leaching losses of sprinkler-applied nitrogen, however, can still be substantial if too much water is applied during the growing season. If water applications are based on scientific irrigation scheduling procedures, losses of mobile nutrients applied through sprinkler systems will be reduced.

There is no need for a split application of mobile nutrients with sprinkler irrigation on either medium- or fine-textured soils. Use of proper water management practices alone will reduce deep percolation and nutrient losses on these soils during the growing season. It should be noted, however, that the application of excessive quantities of mobile nutrients may leave residual amounts that are subject to leaching during the winter and spring.

Relatively Immobile Nutrients Under Sprinkler Irrigation

The management practices with the relatively immobile nutrients under sprinkler irrigation is the same as that for surface irrigation methods. These nutrient fertilizers can be applied whenever they can be incorporated into the soil. Placement practices that promote the efficient use of these nutrients by plants increases their effectiveness and limits nutrient build-up. The control of runoff and erosion will limit pollution problems from the less mobile nutrient sources.

Specific Nutrient/Water Management Situations

When feasible, nitrogen fertilizers should be applied to irrigated lands when potential excessive runoff from rainfall is minimal. A heavy rainfall immediately following an irrigation will result in nitrate leaching, especially in sandy soils, even if the irrigation application is perfect in amount and timing. Losses of mobile nutrients under these conditions may require changes in methods, forms, or time of application.

Leaching hazards with surface irrigation systems are somewhat greater than with sprinkler systems because there generally is more water applied per irrigation under surface irrigation. Slow release forms of the more mobile fertilizers could be used as an option under these situations.

The selection of nutrient management options can be based on soil and plant tissue analyses. Soil and plant tests determine how much of which nutrients are needed, as well as the timing of application in specific situations. Soil testing and the use of recommended nutrient rates can be an important step in reducing pollution from fertilizers. However, nutrient losses probably cannot be reduced to zero levels if crop production is to be maintained at present levels.

PESTICIDE MANAGEMENT

Pesticides are used to control a pest or pests in a crop on a particular site at a particular time. When properly used and managed, pesticides are crop production aids that relieve farmers of toilsome work and increase crop yields. When improperly used, pesticides can cause environmental problems which overshadow their potential benefits. Much effort goes into the registration of a pesticide. The U.S. Environmental Protection Agency closely regulates registration and labeling by the manufacturer. Yet, it is the user who is ultimately responsible for proper and discreet use of these materials. The best information on proper use is printed directly on the label. Rates, timing, pests controlled, methods of application, precautions, prohibitions, etc., are there for each user to read and apply to any specific situation. If these instructions are heeded, the risk of pesticide pollution will be minimized from the start. That's why emphasis should be placed on reading and following label instructions.

Principal factors affecting pesticides in irrigation return flow are soil texture (with associated organic matter content) and the adsorptivity characteristics of the individual pesticides. These were discussed in Section 2. Most pesticides are found both in the water and adsorbed to the sediments. The stronger the adsorption of the pesticide, the more likely it is to move with the sediment. Reduced movement of both water and sediment will have an impact on reducing pesticide losses, but the water phase usually accounts for most pesticide movement. In coarse-textured soils, percolation is of greatest concern. In fine-textured soils, runoff is more likely.

In Iowa's base report (Harmon and Duncan, 1978), estimated percentages of applied pesticides dissolved in runoff water which reached surface streams were 0 to 1 percent for the weakly adsorbed pesticides, 0 to 5 percent for the moderately adsorbed, and 0 to 0.5 percent for the strongly adsorbed. (A pesticide that is strongly adsorbed onto soil colloids is less likely to be found dissolved in runoff water and more likely transported by sediments.) The percentages transported by sediments were estimated at 0 to 0.1 percent for the weakly adsorbed, 0 to 1 percent for the moderately adsorbed, and 0 to 2 percent for the strongly adsorbed pesticides. Under very unusual soil-rainfall-pesticide conditions, these values could quadruple. Wauchope (1978) states that for most commercial pesticides, total losses are 0.5 percent or less of the amounts applied unless heavy rainfall occurs within one to two weeks after application. Pesticides formulated as wettable powders are lost more readily than other formulations. On slopes up to 10 percent, losses of these pesticides are estimated at 2 percent; on slopes over 10 percent, pesticide losses are estimated at 5 percent.

Practices which reduce the need for a pesticide application or which increase the effectiveness of the application and allow a lower application rate reduce the risk of movement outside the area of application. The control of water loss is the key to reducing pesticide losses. Even the least persistent pesticide will move if water runoff occurs shortly after application. Because rainfall amount and intensity are unpredictable, some losses may occur under even the best management systems. The goal should be loss reduction to maintain water quality while pest management practices are kept flexible enough to fit specific situations.

Management options which may affect pesticide losses in water and sediments are given in Table 46. Those management practices which can reduce runoff or percolation losses are given a moderate or substantial impact rating. A low rating implies that the overall impact is estimated to be minor or non-existent under normal conditions. Where extreme conditions such as high soil slope, an intense storm soon after application which produces large

TABLE 46. MANAGEMENT PRACTICES TO REDUCE PESTICIDE CONTRIBUTIONS IN IRRIGATION RETURN FLOWS AND THEIR RATED POLLUTION REDUCTION [1]

Management practice	Coarse-textured soils (Sands to loamy sands)						Medium-textured soils (Loams to silt loams)						Fine-textured soils (Silty clays to clays)					
	Deep percolation			Surface water runoff			Deep percolation			Surface water runoff			Deep percolation			Surface water runoff		
	W[2]	M[3]	S[4]	W	M	S	W	M	S	W	M	S	W	M	S	W	M	S
Irrigation and soil management[5]	S	S	L	L	L	L	M	L	L	S	S	M	L	L	L	S	S	S
Timing of irrigation	M	M	L	L	L	L	L	L	L	M	M	L	L	L	L	M	M	L
Reduce excessive treatment	M	L	L	L	L	L	L	L	L	M	M	L	L	L	L	M	L	L
Use of alternative pesticide	M	M	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Apply optimum dosage for pest	M	M	L	L	L	L	L	L	L	M	L	L	L	L	L	M	L	L
Optimum timing of application	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Optimum placement of pesticide	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	M	L
Application techniques	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Pesticide formulation	L	L	L	L	L	L	L	L	L	S[6]	S[6]	L	L	L	L	S[6]	S[6]	L
Alternative controls	S	S	L	L	L	L	M	L	L	S	S	M	L	L	L	S	S	S

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[1] Rating to reduce pesticide pollution represents estimated potential impact, not necessarily feasibility of practices:

L - Low impact (0-10 percent); M - Moderate impact (10-50 percent); S - Substantial impact (over 50 percent)

[2] W - Weakly Adsorbed Pesticides

[3] M - Moderately Adsorbed Pesticides

[4] S - Strongly Adsorbed Pesticides

[5] Refer to Tables 43 and 44.

[6] For wettable powders

runoff, careless application technique, poor judgment, etc., are involved, the impact may be higher. The influences of these management practices were rated according to their ability to reduce pollution from the 1 to 5 percent level that may be occurring over a broad region. In certain situations, the impact may be higher or lower depending on the circumstances. If present practices are well-managed, current losses may be negligible. On the other hand, poor management can allow high losses which could be substantially reduced by the adoption of better practices. Specific conditions will dictate the ultimate impact of these practices. Table 46 should be viewed as an aide to identifying management practices which will influence pesticide movement in specific soil/pesticide groupings. Impact ratings are broadbased and may not adequately describe local situations.

Irrigation and Soil Management

Practices which help retain the soil and water substantially reduce pesticide losses. These would be expected to help to the same degree that they are rated for reducing deep percolation and runoff, as discussed in earlier sections (Tables 43 and 44). Furthermore, the topsoil, because of higher populations of micro-organisms and greater chemical activity, has the greatest potential to decompose pesticides. Once removed from the topsoil, the decomposition rate decreases and persistence increases.

In general, fine-textured soils with a relatively greater amount of organic matter have greater potential for pesticide decomposition than coarse-textured soils. However, the former also have greater adsorptive capacity and slower water infiltration rates with the result that pesticide pollution potential from runoff and erosion is greater from fine-textured soils. On the other hand, deep percolation is a greater risk in coarse-textured soils.

Excessive Treatment

When pesticides are applied more frequently than necessary or used as preventative treatments, pollution risk is increased. The cost of a pesticide treatment considerably reduces this type of activity in the crops under consideration. In any case, excessive applications should be avoided. Helping the grower identify potential pest problems and determining when pesticides should be applied is a major activity of many consultants and specialists. This concept is embodied in integrated pest management (IPM), although the term has broader applications. To date, insect pests have received major attention in IPM studies because of the ability of these pests to proliferate rapidly. During the crop's growth, the populations of destructive insects are monitored and control techniques applied if and when needed to control the insect and produce the crop. In some cases, natural enemies may be sufficient to hold the insect in check while insecticides may be essential at other times. The same concept works for weeds, diseases, and other pests, though weeds are more predictable and emergency control measures for diseases are often not available.

Pesticides are an important part of most IPM programs because they are immediately effective in slowing or controlling the pest. However, they should be used only as needed and not used indiscriminately. This type of program has been successful in reducing the numbers of insecticide applications required in some crops, especially cotton. The key is that the pests are monitored and a pesticide is only used if and when needed for maximum benefit. Though not useable in all situations, the concept is sound and should be used where applicable. Avoiding the wholesale use of pesticides as preventive treatments will reduce the pollution potential of pesticides, particularly in those situations where percolation or runoff are most likely to present problems.

Alternative Pesticides

Once the Environmental Protection Agency has approved a pesticide label, then on-farm selection must be made based on the pesticide's ability to control a specific pest in a specific situation. Where suitable alternatives exist, persistence and adsorption characteristics should be considered. It is possible that the use of less persistent pesticides may result in a compensating increase in the number of applications required to provide effective control. In cases where this is not true, then the use of less persistent pesticides will reduce pollution potential. Where deep percolation is more likely (coarse-textured soils), a pesticide that is strongly adsorbed onto soil colloids will leach less than a weakly adsorbed pesticide.

While this option may be effective in reducing pesticide movement, suitable alternative pesticides to control the pest in a particular situation are not always available. Cancellation of registration for many of the chlorinated hydrocarbon insecticides has lessened the impact of this alternative.

Optimum Dosage

Applying the optimum dosage for the pest will result in the best benefit-to-risk ratio. Overdosage will certainly increase the amount that is available for runoff or percolation, and underdosage may force retreatment which would increase the total amount applied. Dosage is most likely to affect weakly adsorbed pesticides since their loss with water can happen so readily. Persistence is also a function of dosage. Label instructions for optimum dosage should be followed.

Optimum Timing

A pest is usually most vulnerable to a pesticide at some particular point in its life cycle. By applying the pesticide at that time, both effectiveness and efficiency of the pesticide is increased. A reduction of both the amount needed and the frequency of application is thereby possible.

The time interval between pesticide application and irrigation should be considered to avoid a pollution event. Normally, the two-week interval immediately after application is a critical period. Application of foliar pesticides should be avoided for 8 to 24 hours before periods of rain and sprinkler irrigation. This will maximize effectiveness and minimize plant leaf washoff that can accumulate in runoff and soil particles. The impact of optimum pesticide application timing shown in Table 46 is estimated to be low because large differences in timing of pesticide applications normally do not occur.

Optimum Placement

If a pesticide is optimally placed, its maximum effectiveness for pest control is realized. Unless the pest comes into contact with the pesticide, the pesticide is wasted and repeated applications will be necessary, particularly for short residual pesticides.

Soil incorporation of wettable powder pesticide formulations has been shown to decrease washoff from the soil. In this case, moderate impact may be realized on fine-textured soils (Table 46).

Application Techniques

Techniques which place the highest proportion of the applied pesticide dosage on the target are the most efficient for controlling a pest. A less efficient method may require higher dosages to compensate for losses, thereby increasing pollution potential. Method of application, spray volume, nozzle selection, equipment calibration, sprayer operation, marking systems, and climatic factors such as wind conditions can significantly affect application efficiency. Aerial application efficiency is undoubtedly subject to greater variation because of lower spray volumes and higher droplet release heights than most ground application equipment. Application directly to the pest or host crop is probably the most efficient technique, but not always feasible. Soil incorporation is essential for the performance of some pesticides and any delay can mean significant loss of the pesticide and poor pest control.

Application techniques require careful attention, because any practice that reduces application efficiency may result in poor pest control and a possible need to retreat. Although careful attention to sound application techniques is vital for effective pesticide usage and pollution reduction, it is unlikely that the overall pollution reduction will exceed 10 percent, except where proper techniques are being ignored or slighted.

Pesticide Formulation

Wettable powder formulations of pesticides are readily lost if the first rainfall or irrigation after treatment produces runoff (Wauchope, 1978). Where alternative formulations are available for a pesticide, switching to an emulsion, suspension, or granule could substantially reduce runoff losses of the weakly or moderately adsorbed pesticides. Of the major use pesticides in Tables 29 and 30, atrazine, cyanazine, and propazine are sold as wettable powders but are available as suspensions too.

Alternative Controls

Alternative control methods include natural control with predators, crop resistance, crop rotation, crop competition, cultivation, tillage, planting date, etc. All control alternatives should be considered and pesticides used only when needed. This does not necessarily mean that pesticide use will decline, but could insure that indiscriminate use will be reduced. In situations where pesticide percolation or runoff present high risks the decision to use an alternative pest control method may have a substantial impact on pollution reduction; however, it is unlikely that large-scale replacement of pesticides will occur unless wholesale changes are made in society. The trends to larger farms, fewer farm laborers, high labor costs, high production costs, monocultures, and reduced tillage has brought about increased use of pesticides for pest control. These trends are likely to continue though at a decreasing rate.

SECTION 4

ECONOMIC FEASIBILITY OF FARM MANAGEMENT ALTERNATIVES TO REDUCE POLLUTION

by
R. J. Supalla and R. R. Lansford

INTRODUCTION

Policies designed to reduce pollution from irrigated agriculture should consider the impact each alternative approach will have on both water quality and the income of agricultural producers. Policies which would have a positive effect on water quality and a neutral or positive effect on the agricultural economy obviously are desirable. On the other hand, policies which would have a positive effect on water quality but a negative effect on the economy are appropriate only if two conditions are met. First, it should be the least costly method of achieving the desired result and, second, the improvement in water quality should be worth more to society than the cost of achieving it.

This section provides information which can be used to determine whether the above conditions hold for a selected array of major management alternatives. The basic intent is to provide an indication of how the implementation of these management options would affect the economic well-being of agricultural producers. No attempt is made to answer the broad economic question of whether any given action is justified in terms of a total array of costs and benefits. An answer to this broad economic question would require quantification of the social value of water quality improvements, a task which was outside the scope of this study. Thus, the approach used herein assumes that implementing selected farm management improvements would enhance water quality and proceeds to assess the economic feasibility of making such management adjustments.

MANAGEMENT OPTIONS TO BE EVALUATED

Available research resources are not sufficient for presenting an economic assessment of all available options for reducing pollution from irrigated agriculture. Therefore, this analysis treats only those options which were determined to have potentially large economic effects and/or which were believed to be the ones most likely to be seriously considered by policy makers. With these criteria in mind, the following management options were selected for analysis: (1) alternative types of irrigation systems (surface, with and without reuse, automated gated pipe and center pivot sprinklers); (2) irrigation scheduling (quantity and timing of water applications); (3) surface system water application procedures (length of run, and cutback); (4) reductions in water applications below full irrigation requirements; (5) fertilization practices; (6) pesticide usage; and (7) reduced tillage. The economic effects associated with each of these options are discussed below.

ANALYTICAL PROCEDURES

The effect of management changes on producer incomes could be analyzed in several ways, but the least difficult and most easily understood approach is enterprise budgeting (Appendix C). This technique permits the estimation of the differences in costs and returns of various management practices for one or more farm situations.

The first step in the budget analysis was the selection of the appropriate farm situations to be analyzed. This was the critical step in the analysis because cost and return estimates are often significantly affected by situational parameters such as location and size of farm, water source (well or canal), depth to water, crops produced, level of managerial skill, etc. For this analysis, two hypothetical farm situations were selected; one "typical" of the Southern Plains, and another "typical" of the Central Plains.

For the Southern Plains, the hypothetical farm situation was assumed to consist of: a 323.8 hectare completely-irrigated farm producing about 80.9 hectares of cotton, corn, grain sorghum and wheat; irrigation was from 2.47 cubic meters per minute wells with 68.8 meters of lift and natural gas-powered pumps; soils were medium-textured with 0 to 1 percent slope, and above average management was assumed. 1/ It was further assumed that the model farm contained some nonirrigated lands (either summer fallow wheat or rangeland) which could be irrigated if sufficient water were available, and that the acreage tracts for the farm were laid out in a manner which permitted either surface or center pivot irrigation. This permitted the assumption that total irrigated acreage and the average annual cropping patterns were the same (center pivot corners would be used for the nonirrigated options) when assessing the economics of alternative types of irrigation systems.

The hypothetical situation analyzed for the Central Plains consisted of: a 315.6 hectare farm producing 157.8 hectares of irrigated corn, 52.6 hectares of irrigated alfalfa, 52.6 hectares of irrigated grain sorghum and 52.6 hectares of dryland grain sorghum; irrigation was from 3.04 cubic meters per minute wells, with 30.5 meters of lift and diesel-powered pumps; soils were

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1/ The "above average" management assumption is reflected in the cultural practices, fertilization rates and expected yields employed in the budgets. However, this does not appreciably influence the estimated cost of irrigating with alternative systems, and therefore has little influence on the conclusions which follow from the analysis.

medium-textured with 0 to 1 percent slope; and above average management was assumed. It was further assumed that the model farm was laid out in acreage tracts which would permit either surface or center pivot irrigation, with total irrigated acreage and the average annual cropping pattern remaining the same. When the economics of a center pivot sprinkler were considered, it was assumed that dryland grain sorghum was planted in the corners.

Cost and return estimates for the above farm situations were developed for use in analyzing alternative management practices using the Agricultural Computer Network (AGNET) crop budget generator at the University of Nebraska-Lincoln. See Appendix C for details regarding the machinery complements, input prices and other cost factors used for both hypothetical farm situations.

RESULTS - WATER MANAGEMENT OPTIONS

Costs and Returns for Different Types of Irrigation Systems

One of the major policy alternatives available for reducing pollution from irrigated agriculture is encouraging a change from a type of irrigation system which may be causing excessive runoff or deep percolation, under a given set of circumstances, to one which would improve water management and subsequently reduce the pollutants (sediments, nutrients, salts, etc.) entering the water system. Within the Great Plains one can find nearly every available type of irrigation system, but some are used more than others and, in some instances, there are no appreciable differences in costs or in water quality. Therefore, only four typical irrigation systems were considered: surface with and without reuse (siphon tubes in the Southern Plains and gated pipe in the Central Plains), automated gated pipe, and center pivot sprinklers.

The economic implications of shifting from one type of system to another were analyzed by estimating the net returns for each irrigation system, by crop, for both the Southern and Central model farm situations. This approach provides an estimate of what the net return differences would be if farmers initially installed one type of system instead of another, or if they changed irrigation systems when their current one was fully depreciated. The analysis does not address the cost differences associated with abandoning a partially depreciated irrigation system with a low salvage value and installing another type. This omission is of little significance, however, as long as we accept the likely proposition that farmers will not be required to change systems before their existing ones are fully depreciated.

Southern Plains--

Net return differences between irrigation systems can occur because of differences in irrigation costs, tillage practices and/or gross returns (yields). However, given that good management and sufficient water availability have been assumed, it seems reasonable to expect that the yields (gross returns) for all types of irrigation systems would be the same. Also, over much of the Southern Plains, tillage practices are very similar for the types of irrigation systems under consideration. This means that net returns vary between irrigation systems only to the extent that irrigation costs vary, as illustrated in Tables 47 to 50.[1]

In the case of corn (Table 47), the least costly irrigation system is furrow irrigation (siphon tubes) with reuse. However, there is little difference in net returns between furrow irrigation with and without reuse pits. The with and without reuse differences are small, because with reuse one is able to produce with less water (80 percent irrigation efficiency instead of 60 percent). Consequently, variable costs are reduced by enough ($12.21 per hectare) to more than offset the increase in investment costs due to the reuse pit and associated equipment ($7.20 per hectare).

The automatic gated pipe alternative, in the case of corn, generates a per hectare net return of $28.76 below the furrow irrigation with reuse pit alternative. This difference occurs primarily because shifting to automated gated pipe increases irrigation fixed costs by $35.82, while irrigation labor costs are reduced by only $7.90 per hectare.

The center pivot sprinkler is by far the least profitable alternative. In the case of corn, center pivot irrigation costs $117.84 per hectare more than the most attractive alternative, furrow irrigation with reuse. Center pivot costs are higher primarily because of the increased fuel costs to pressurize the system and the investment cost of the pivot and associated equipment. Irrigation labor and land leveling charges are somewhat lower, but they do not come close to compensating for the cost components which are increased.

Cotton is similar to corn in that furrow irrigation with reuse is the least costly alternative ($149.94 per hectare) and there is little difference in net returns between the furrow irrigation with and without reuse pits (Table 48). The irrigation variable costs are $11.86 per hectare lower with furrow irrigation when reuse pits are used, because irrigation water pumpage is reduced five hectare-centimeters. Fixed costs are increased by $7.19 because of the investment in the reuse pit and associated machinery. The resulting net difference due to reuse is only $4.67.

Net returns from cotton production using automatic gated pipe or center pivot irrigation are, respectively, $29.88 and $118.39 per hectare below that expected from furrow irrigation with reuse pits. These differences occur in the case of cotton for the same reasons discussed above in the case of corn.

Grain sorghum follows a pattern for the four alternative irrigation systems that is similar to corn and cotton (Table 49). Again, furrow

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[1] It could be argued that purchased inputs such as fertilizer will vary between options because of such things as less leaching, but this effect was ignored on the grounds that it would be very small and, in any case, difficult to estimate.

TABLE 47. PER HECTARE COSTS AND RETURNS FOR CORN (GRAIN) BY TYPE OF IRRIGATION SYSTEM FOR THE SOUTHERN HIGH PLAINS, 1979

Cost and return items	Type of irrigation system			
	Furrow irrigation			Center pivot sprinkler
	without reuse pits	with reuse pits	automatic gated pipe	
	- - - - - - - - dollars per hectare	- - - - - - - - -		
Purchased inputs	139.19	139.19	139.19	139.19
Labor, except irrigation	25.45	25.45	25.45	25.45
Variable machinery costs	167.21	167.21	167.21	167.21
Fixed machinery costs	41.49	41.49	41.49	41.49
Other costs 1/	38.62	38.10	38.67	41.83
Irrigation 2/				
Labor	21.74	21.74	13.84	5.93
Variable machinery	64.87	52.66	53.40	102.25
Fixed machinery	69.80	77.00	112.82	158.78
Interest on operating expenses	5.76	4.94	4.47	7.19
Total irrigation	162.17	156.34	184.53	274.15
Summary				
Total cost	574.13	567.78	596.54	689.32
Gross returns 3/	722.62	722.62	722.62	722.62
Net returns to land and management	148.49	154.84	126.08	33.30

1/ Includes interest on operating capital and an overhead charge.

2/ The amount of water applied to the root zone was assumed to be 33.5 centimeters for each system. The gross applications were 55.9 centimeters for furrow without reuse, 41.9 centimeters for furrow with reuse and center pivot, and 39.4 centimeters for automatic gated pipe.

3/ Yield: 8156 kilograms; price: 8.86 cents per kilogram

TABLE 48. PER HECTARE COSTS AND RETURNS FOR COTTON BY TYPE OF IRRIGATION SYSTEM FOR THE SOUTHERN HIGH PLAINS, 1979

Cost and return items	Type of irrigation system			
	Furrow irrigation			
	without reuse pits	with reuse pits	automatic gated pipe	Center pivot sprinkler
	dollars per hectare			
Purchased inputs	59.30	59.30	59.30	59.30
Labor, except irrigation	20.88	20.88	20.88	20.88
Variable machinery costs	202.00	202.00	202.00	202.00
Fixed machinery costs	57.23	57.23	57.23	57.23
Other costs 1/	33.19	32.59	33.09	35.93
Irrigation 2/				
Labor	19.77	19.77	12.85	5.93
Variable machinery	59.75	48.63	49.49	93.65
Fixed machinery	69.80	77.00	112.82	158.78
Interest on operating expenses	5.29	4.55	4.15	6.42
Total irrigation	154.61	149.94	179.32	264.78
Summary				
Total cost	527.21	521.94	551.82	640.12
Gross returns 3/	892.42	892.42	892.42	892.42
Net return to land and management	365.21	370.48	340.60	252.30

1/ Includes interest on operating capital and an overhead charge.

2/ The amount of water applied to the root zone was assumed to be 30.5 centimeters for each system. The gross applications were 50.8 centimeters for furrow without reuse, 38.1 centimeters for furrow with reuse and center pivot, and 46 centimeters for automatic gated pipe.

3/ Yield: lint, 616.5 kilograms; cottonseed, 874.2 kilograms;
Price: $1.26 per kilogram lint, $132.27 per tonne cottonseed

TABLE 49. PER HECTARE COSTS AND RETURNS FOR GRAIN SORGHUM BY TYPE OF IRRIGATION SYSTEM FOR THE SOUTHERN HIGH PLAINS, 1979

Cost and return items	Type of irrigation system: Furrow irrigation without reuse pits	Furrow irrigation with reuse pits	Furrow irrigation automatic gated pipe	Center pivot sprinkler
	dollars per hectare			
Purchased inputs	88.46	88.46	88.46	88.46
Labor, except irrigation	25.45	25.45	25.45	25.45
Variable machinery costs	107.66	107.66	107.66	107.66
Fixed machinery costs	41.49	41.49	41.49	41.49
Other costs 1/	25.25	24.68	25.18	27.95
Irrigation 2/				
Labor	19.77	19.77	12.85	5.93
Variable machinery	57.18	46.45	47.54	89.35
Fixed machinery	69.00	77.00	112.82	158.78
Interest on operating expenses	5.11	4.40	4.03	6.33
Total irrigation	151.06	147.62	177.24	260.39
Summary				
Total cost	439.37	435.36	465.48	551.40
Gross returns 3/	434.89	434.89	434.89	434.89
Net returns to land and management	-4.48	-.47	-30.59	-116.51

1/ Includes interest on operating capital and an overhead charge.

2/ The amount of water applied to the root zone was assumed to be 29.0 centimeters for each system. The gross applications were 48.3 centimeters for furrow without reuse, 36.1 centimeters for furrow with reuse and 34.0 centimeters for automatic gated pipe.

3/ Yield: 5604.2 kilograms; price: 7.76 cents per kilogram

TABLE 50. PER HECTARE COSTS AND RETURNS FOR WHEAT BY TYPE OF IRRIGATION SYSTEM FOR THE SOUTHERN HIGH PLAINS, 1979

Cost and return items	Type of irrigation system: Furrow irrigation: without reuse pits	with reuse pits	automatic gated pipe	Center pivot sprinkler
	- - - - - - - dollars per hectare	- - - - -	- - - - -	- - - - -
Purchased inputs	66.72	66.72	66.72	66.72
Labor, except irrigation	6.38	6.38	6.38	6.38
Variable machinery costs	46.70	46.70	46.70	46.70
Fixed machinery costs	18.88	18.88	18.88	18.88
Other costs 1/	16.65	16.06	16.14	17.96
Irrigation 2/				
Labor	18.78	18.78	11.86	5.93
Variable machinery	57.18	46.45	47.54	89.35
Fixed machinery	69.00	77.00	112.82	158.78
Interest on operating expenses	3.78	3.09	3.14	6.33
Total irrigation	148.74	145.32	175.36	260.39
Summary				
Total cost	304.07	300.06	330.18	417.03
Gross returns 3/	296.44	296.44	296.44	296.44
Net returns to land and management	-7.63	-3.62	-33.74	-120.59

1/ Includes interest on operating capital and overhead charge.

2/ The amount of water applied to the root zone was assumed to be 29.0 centimeters for each system. The gross applications were 48.3 centimeters for furrow without reuse, 36.2 centimeters for furrow with reuse and 34.0 centimeters for automatic gated pipe.

3/ Yield: 2690 kilograms; price: 11.02 cents per kilogram irrigation with reuse pits is the most profitable alternative, generating a net return to land and management of -$0.47 per hectare with total irrigation costs of $147.62. Furrow irrigation without reuse, automated gated pipe, and center pivots were estimated to be $4.01, $30.12 and $116.04 per hectare less profitable than furrow with reuse, respectively.

Wheat followed the same economic pattern as grain sorghum, with the furrow irrigation without reuse pits alternative being the most profitable and the center pivot being the least profitable alternative (Table 50). Indeed, the differences were the same, because the amount of water applied was assumed to be the same for both crops.

To summarize for the Southern Plains, furrow irrigation with reuse pits appears to be the most viable alternative for reducing deep percolation and runoff of irrigation water. Gross irrigation water applications can be reduced by about 20 percent below the alternative of furrow irrigation without reuse pits with a slight improvement in net returns for all crops. Gross irrigation water applications can be reduced another 5 to 10 percent by going to the automatic gated pipe system; however, net returns on the average are reduced 20 to 25 percent primarily because of the larger capital investment requirement for the automatic gated pipe system. The center pivot system required about the same amount of irrigation water be pumped as that required for the furrow irrigation with reuse pit, but the per hectare net returns are greatly reduced.

Central Plains--

The results of the analysis of alternative irrigation systems in the Central Plains (Tables 51 to 53) are quite similar to those for the Southern Plains, except the magnitude of the differences between irrigation systems tends to be smaller. The principal regional differences occur because lifts and water application levels are generally lower and land leveling charges higher in the Central Plains. As was the case for the Southern Plains, all variations in net returns for each crop considered are due to variations in irrigation costs, because tillage practices and purchased inputs do not vary by type of irrigation system.

Gated pipe with reuse was found to be the least costly system for all crops in the Central Plains example, but the with and without reuse cost differences were very slight for all crops (Tables 51 to 53). Estimated total irrigation costs with reuse were $160.71, $149.05 and $140.55 per hectare for alfalfa, corn and grain sorghum, respectively, whereas without reuse they were $168.20, $154.86 and $144.55 per hectare. The differences are small, because with reuse one is able to produce with less water (80 percent irrigation efficiency instead of 60 percent) and consequently variable costs are reduced by enough to essentially offset the investment costs of reuse pit and associated equipment. The variations across crops are primarily due to variations in the amount of water required.

For all crops, automated gated pipe irrigation is considerably less expensive than center pivot sprinklers and only slightly more expensive than gated pipe with reuse. The automated system was also more expensive than

TABLE 51. PER HECTARE COSTS AND RETURNS FOR ALFALFA BY TYPE OF IRRIGATION SYSTEM CENTRAL GREAT PLAINS, 1979

Cost and return items	Type of irrigation system			
	Gated pipe without reuse pits	Gated pipe with reuse pits	Automatic gated pipe	Center pivot sprinkler
	- - - - - - - - - dollars per hectare - - - - - - - - -			
Purchased inputs	497.90	497.90	497.90	497.90
Labor, except irrigation	18.68	18.68	18.68	18.68
Variable machinery costs	165.55	165.55	165.55	165.55
Fixed machinery costs	27.28	27.28	27.28	27.28
Other costs [1]	81.34	80.92	81.07	84.75
Irrigation [2]				
Labor	14.83	14.83	11.12	7.41
Variable machinery	53.67	45.54	43.86	108.28
Fixed machinery	95.16	96.34	109.32	131.97
Interest on operating expense	4.55	4.00	3.66	7.68
Total irrigation	168.20	160.71	167.95	255.35
Summary				
Total cost	958.95	951.04	958.43	1049.51
Gross return [3]	965.79	965.79	965.79	965.79
Net returns to land and management	6.84	14.75	7.36	-83.72

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[1] Includes interest on operating capital and an overhead charge.

[2] The amount of water applied to the root zone was assumed to be 40.6 centimeters for each system. The gross applications were 67.8 centimeters for gated pipe without reuse, 50.8 centimeters for gated pipe with reuse and 47.8 centimeters for automatic gated pipe and center pivot systems.

[3] Yield of 14.6 tonnes per hectare at $66.15 per tonne.

TABLE 52. PER HECTARE COSTS AND RETURNS FOR CORN BY TYPE OF IRRIGATION SYSTEM CENTRAL GREAT PLAINS, 1979

Cost and return items	Type of irrigation system: Gated pipe without reuse pits	Gated pipe with reuse pits	Automatic gated pipe	Center pivot sprinkler
	- - - - - - - - dollars per hectare			- - - - - - - -
Purchased inputs	139.19	139.19	139.19	139.19
Labor, except irrigation	20.66	20.66	20.66	20.66
Variable machinery costs	58.64	58.64	58.64	58.64
Fixed machinery costs	88.14	88.14	88.14	88.14
Other costs [1]	25.28	24.93	25.06	28.05
Irrigation [2]				
Labor	11.86	11.86	8.90	5.93
Variable machinery	44.11	37.56	36.35	88.19
Fixed machinery	95.16	96.34	109.32	131.97
Interest on operating expenses	3.73	3.29	3.01	6.25
Total irrigation	154.86	149.05	157.57	232.34
Summary				
Total cost	486.77	480.61	489.26	567.02
Gross returns [3]	722.62	722.62	722.62	722.62
Net returns to land and management	235.85	242.01	233.36	155.60

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[1] Includes interest on operating capital and an overhead charge.

[2] The amount of water applied to the root zone was assumed to be 32.5 centimeters for each system. The gross applications were 54.1 centimeters for gated pipe without reuse, 40.6 centimeters for gated pipe with reuse and 38.4 centimeters for automatic gated pipe and center pivot systems.

[3] Yields of 8156 kilograms per hectare at 8.86 cents per kilogram.

TABLE 53. PER HECTARE COSTS AND RETURNS FOR GRAIN SORGHUM BY TYPE OF IRRIGATION SYSTEM CENTRAL GREAT PLAINS, 1979

Cost and return items	Type of irrigation system: Gated pipe without reuse pits	Gated pipe with reuse pits	Automatic gated pipe	Center pivot sprinkler
	- - - - - - - - - dollars per hectare			- - - - - - - - -
Purchased inputs	75.86	75.85	75.86	75.86
Labor, except irrigation	17.77	17.77	17.77	17.77
Variable machinery costs	37.88	37.88	37.88	37.88
Fixed machinery costs	73.78	73.78	73.78	73.78
Other costs 1/	14.65	14.38	14.58	16.85
Irrigation 2/				
Labor	11.86	11.86	8.90	5.93
Variable machinery	34.45	29.58	28.66	68.08
Fixed machinery	95.16	96.34	109.32	131.97
Interest on operating expense	3.09	2.77	2.50	4.92
Total irrigation	144.55	140.55	149.38	210.90
Summary				
Total cost	364.49	360.21	369.25	433.04
Gross returns 3/	487.06	487.06	487.06	487.06
Net returns to land and management	122.57	126.85	117.81	54.02

1/ Includes interest on operating capital and an overhead charge.

2/ The amount of water applied to the root zone was assumed to be 24.4 centimeters for each system. The gross applications were 40.6 centimeters for gated pipe without reuse, 30.5 centimeters for gated pipe with reuse and 28.7 centimeters for automatic gated pipe and center pivot.

3/ Yield: 6,276.6 kilograms; price: 7.76 cents per kilogram gated pipe without reuse except in the case of alfalfa. It is more costly than gated pipe with reuse, because the relatively high investment costs associated with the system are not entirely offset by lower labor and variable machine costs. When compared to gated pipe without reuse, however, the improved efficiency of the automated system lowers variable costs enough to more than offset the higher investment costs in the case of high water-using crops such as alfalfa. It also should be noted that automated gated pipe is much more attractive for the Central Plains situation than it is in the Southern Plains. This difference occurs because for the Southern Plains example, automated gated pipe was compared to siphon tubes which are considerably cheaper than gated pipe.

The most costly type of irrigation system for all crops is center pivot sprinklers, costing $255.35 per hectare for alfalfa, $232.34 for corn and $210.90 for grain sorghum. These costs are 50 to 59 percent higher than the least costly options for each crop, due primarily to the additional fuel costs for pressurizing a center pivot and to the cost of the machine itself.

From the above cost analysis it appears that policies to require or encourage different types of irrigation systems as a method of improving water quality could have relatively severe economic consequences. For example, a shift from gated pipe without reuse to center pivot sprinklers would increase production costs (reduce net returns) by $21,033 for the entire farm ($90.56 x 52.6 hectares alfalfa + $80.25 x 157.8 hectares corn + $68.55 x 52.6 hectares grain sorghum).

The only pollution-reducing irrigation system changes which apparently could be implemented without substantial economic losses are the installation of reuse pits or a shift from gated pipe without reuse to automated gated pipe. It was estimated that a shift from gated pipe without reuse to gated pipe with reuse would increase annual net returns by $1,613 ($4.28 x 52.6 hectares + $6.16 x 157.8 hectares + $7.91 x 52.6 hectares = $1,613). This action is therefore clearly desirable from both a water quality and an economic point of view. On the other hand, to go a step further and shift from gated pipe with reuse to automated gated pipe would reduce annual net returns by $2,229. This decrease appears small enough to make automated gated pipe a viable alternative, depending on the magnitude of the potential water quality improvements.

As a final note, it is important to point out that the above analysis assumes equal yields for all irrigation systems. This is probably a reasonable assumption if well capacities are great enough to provide all plant water needs even in dry years. But, if this is not the case, then the more efficient systems would be more attractive economically than depicted above.

Irrigation Scheduling

Another important irrigation management option for improving water quality is irrigation scheduling. Many irrigators apply excess water to their crops because of limited information regarding the amount of water needed at particular times during the season. Excess water applications, which often increase runoff and leaching, can be reduced by following one of several available scheduling techniques.

The financial impact from requiring irrigators to follow a particular scheduling practice depends on the amount of water saved, the cost of scheduling, impact on fertilizer needs, and the yield effect, if any. Individual irrigators will therefore be affected differently, but a good idea of the nature of the financial impact can be obtained by examining two illustrative cases, one for the Central Plains and another for the Southern Plains.

Improved irrigation scheduling appears to have substantial potential for improving water quality in the Central Plains where water is plentiful and where over-irrigating is quite prevalent. For example, a study of irrigation practices in the Benedict area of east central Nebraska revealed that irrigators who followed technical scheduling procedures applied an average of 34.8 centimeters, which was estimated to be 35 percent less than the average for all irrigators in the area (Noffke, et al., 1975). Assuming a diesel-powered gravity system and 15.24 meters of head, the cost savings from pumping 18.8 (53.59 - 34.8) fewer centimeters per hectare amounts to about $25.29 per hectare. In addition, it has been estimated that a savings of as much as 56.0 kilograms per hectare of nitrogen can be obtained with scheduling and at the current price of 22 cents per kilogram, this amounts to a savings of $12.32 per hectare. Therefore, given no change in yields and assuming a scheduling service can be purchased for $6.18 per hectare, the net gain from scheduling in our Central Plains example totals $31.43 per hectare ($25.29 + $12.32 - $6.18 = $31.43).

For the Southern Plains, the issues associated with scheduling are the same, but the potential impacts are less. Impacts are likely to be less because water is less plentiful and thus there is generally less over-irrigating. In contrast to the Central Plains illustration where a 35 percent reduction in water use was assumed, the potential savings in the Southern Plains is likely to be 10 percent or less. Assuming a natural gas-powered gravity system without reuse and 68.6 meters of head, the cost savings from pumping 5.08 centimeters less (about 10 percent) would be only $5.88 per hectare. Likewise, the reductions in nitrogen leaching would likely be proportionately less, perhaps 6.8 kilograms, for a per hectare fertilizer savings of $1.50. Thus, a "typical" net gain from scheduling in the Southern Plains totals only $1.20 per hectare ($5.88 + $1.50 - $6.18 = $1.20).

It seems reasonable to conclude from the foregoing analyses that irrigation scheduling will usually have a positive economic impact on irrigators and that, especially for the Central Plains, this impact could be very substantial. Thus, scheduling is an attractive management practice from both a water quality and an economic point of view.

Reduce Water Applications Below Full Irrigation Requirements

The foregoing analysis of scheduling treats the economic consequences of policies to avoid water applications in excess of crop needs. It is possible, although not necessarily desirable, to go a step further and reduce water applications below crop needs. This potentially could improve water quality beyond what is possible with scheduling to meet crop needs, but yield reductions are likely to make the economic consequences quite severe.

Yield decreases from reducing water applications below crop needs will vary widely from region to region and by crop. However, one can get an idea of the potential magnitude of these effects by examining one situation for which the necessary data are available. John Shipley of Texas A & M University estimated yield/water-applied relationships for wheat, corn and grain sorghum in the Northern High Plains of Texas (Shipley, 1977; Larsen, 1978).[1] By using his equations to approximate yield reductions from less water use and given the available data on variable irrigation costs for ditch irrigation with reuse, one can assess the net economic effect from reducing water applications below crop needs.

Shipley found that the production function for corn was of the form

$$Y = 980.8 + 234.65X - 1.56X^2 \tag{3}$$

where Y = yield in kilograms per hectare and X = total water applied in centimeters. This means, for example, that if gross water applied to corn was reduced from 61.0 to 40.6 centimeters, yield would decrease by 1,553.54 kilograms per hectare. At 8.86 cents per kilogram, this is a reduction in gross returns of $137.64. Total costs would be reduced by approximately $46.40 (irrigation variable costs, $23.52; seed, $5.19; and fertilizer, $17.69), for a net economic loss of $91.24 per hectare, or $4.47 per centimeter reduction in water applied.

The corresponding production function for grain sorghum was

$$Y = 2{,}434.1 + 231.5X - 2.59X^2 \tag{4}$$

where Y = yield in kilograms per hectare and X = total water supplied in centimeters. Thus, a reduction in water applied to grain sorghum of from 40.6 to 30.5 centimeters is estimated to reduce yields by 478 kilograms per hectare. At a price of 7.67 cents per kilogram, this reduces gross returns by $36.66 per hectare. Total costs would be reduced by $18.31 (irrigation variable costs, $11.76; fertilizer, $5.34; and seed, $1.21), for a net economic loss of $18.35 per hectare or $1.82 per centimeter reduction in water applied.

In the case of wheat, Shipley's estimated production function is of the form

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[1] The Shipley analysis considered changes in irrigation timing as well as the quantity of water applied, and this is reflected in the estimated yield/water-applied relationships.

$$Y = 1{,}091.3 + 100.8X - .94X^2 \quad (5)$$

where Y = yield in kilograms per hectare and X = total water applied in centimeters. This means that if the water applied to wheat is reduced from 40.6 to 30.5 centimeters, yields decrease by 343 kilograms per hectare, for a reduction in gross returns at 11.02 cents per kilogram of $37.80 per hectare. Production costs would be reduced by $15.69, (irrigation variable costs, $11.76; and fertilizer, $3.93) resulting in a reduction in net returns of $22.11 per hectare, or $2.19 per centimeter reduction in water.

Shipley's analysis indicates quite clearly that the economic losses from reducing water applications below crop needs are quite severe, especially for corn. However, it is important to note that a program which precluded full irrigation of corn would probably result in a substitution of sorghum for corn, making the economic losses less severe than they appear to be from Shipley's analysis. The precise impact would depend on the relative profitability of corn and sorghum, crop rotation constraints and the specific dimensions of any program which prevented full irrigation.

Another factor which policy makers should keep in mind is that the economic impact of reducing water applications below crop needs will probably vary widely by geographic area, soil type, etc. Thus there may be situations where programs to encourage or require less than full irrigation are an economically-feasible means of improving water quality, but given the magnitude of the illustrated consequences, this appears unlikely.

Other Water Management Practices

There are numerous water management practices, in addition to scheduling and reducing water applications below crop needs, which could be used to potentially improve water quality. The most important of these appear to be reducing the length of run and using a cutback system.

Length of Run--

Irrigation efficiency can be increased by reducing the length of field. However, there are some trade-offs that should be considered before recommending that length of run be reduced. The primary trade-off considerations are: (1) increased labor requirements, (2) reduced machinery efficiency, and (3) loss of productive land by increasing the turn row areas. If length of runs are reduced, more irrigation time will be required if for no other reason than because of the increase in the number of irrigation sets. In addition, machine and labor efficiency may be reduced and productive land lost if the tractor operator has to turn around twice as often because of shorter fields. There are methods to reduce the impacts on machinery and loss of productive land but these alternatives tend to be capital intensive. One of the more popular of the alternatives is the use of underground pipe with laterals and hydrants across fields. However, it does not appear that this will save additional irrigation pumpage above furrow irrigation with reuse pits, and it would clearly reduce net returns per hectare because of the capital investment.

Cutback--

The cutback system involves reducing the volume of water being placed on a field when the field is two-thirds to three-quarters irrigated. Typically, siphon tubes or gated pipe are used with this system. The major economic factor associated with this system is the increased amount of labor required. To fully use this system, full-time irrigators may be required. For example, on corn, the hours of irrigation labor per year per acre may almost triple to perhaps three hours per acre. In many areas of the Great Plains it would be almost impossible to find this much temporary labor during the irrigation season. Irrigation water savings would be expected to be in the same magnitude as that for automatic gated pipe. Economically, it appears that it is almost a direct trade-off between fixed capital investment for the automatic gated pipe system and the increased annual irrigation labor costs for a manual system.

ECONOMICS OF REDUCED TILLAGE

One of the practices available for reducing runoff from irrigated lands is reduced tillage. Reduced tillage techniques disturb the soil less than conventional practices and leave more crop residue on the land surface, thus reducing runoff.

The central economic question associated with the reduced tillage option is: how is the profitability of agriculture affected by a shift from conventional to a reduced or conservation tillage system? If net returns are substantially reduced by a shift to conservation tillage, it is probably a feasible means of improving water quality only if large public subsidies are available. On the other hand, if conservation tillage yields are near or equivalent to net returns, it is a near "costless" means of improving water quality. Unfortunately, the answer to this central question will depend on the region, the crop, the type of conservation tillage, and other factors, and it is not possible to consider all situations. Accordingly, this analysis will consider only two illustrative situations as a means of assessing the general magnitude of the impact.

The situations to be considered involve gated pipe and center pivot irrigated corn in the Central Plains. The first situation consists of comparing conventional gated pipe with reuse irrigation (Table 52) with a reduced tillage system. The assumed reduced tillage system differs from conventional tillage in the following ways: two tandem discings are eliminated and replaced by a once-over rotary till-plant operation; one cultivation is replaced by a rotary till operation; and net water application is reduced by 2.54 centimeters. It is further assumed that the tillage shifts occur for all row crops on the model farm and that all other inputs remain the same.

The second illustrative situation consists of comparing conventional center pivot irrigated corn in the Central Plains with a reduced tillage system which differs from the conventional in the following ways: two tandem discings are eliminated and replaced by a rotary till-plant operation;

additional herbicide (broadcast instead of band) is substituted for two cultivations; and net water application is reduced by 5.1 centimeters. Again, it is assumed that this shift occurs for all row crops and that no other changes in the farm operation occur.

The results of the analysis indicate that the gated pipe reduced tillage system yields slightly higher net returns ($5.69 per hectare) than conventional tillage (Table 54). The reduced tillage net returns are higher, because of slight irrigation costs and labor savings. Total machinery costs do not change much because the cost savings from the reduced number of field operations are essentially offset by the need to purchase a new $12,000 rotary tiller. It also should be noted that yields have been assumed constant, whereas in actual practice they could vary by perhaps plus or minus 20 percent.

The results for the center pivot reduced tillage alternative are quite different. They indicate that reduced tillage yields somewhat lower net returns, $140.73 per hectare compared to $155.60. The principle reason for this difference is the $37.06 increase in purchased inputs to meet greater herbicide requirements. Essentially, the slightly lower labor, irrigation and machine costs fail to compensate for the higher herbicide requirement that is necessary for effective weed control. Again, projected yields have been assumed constant.

In general it appears that there are economically-attractive opportunities for adopting reduced tillage in irrigated agriculture. However, the machinery, irrigation, and labor savings are not very great and, therefore, reduced tillage is not attractive in instances where purchased input requirements are considerably higher or where there is a likelihood of negative yield effects. From an economic perspective only, reduced tillage options appear to merit serious consideration, providing considerable caution is exercised for each specific situation.

FERTILIZATION PRACTICES

Another area of management practices related to water quality is that associated with fertilization practices. Problems associated with fertilization can occur in two ways: excessive applications, and application at the wrong time or in the wrong form.

Excessive fertilization occurs when amounts in excess of crop needs are applied because of poor information. Programs to discourage excessive use of fertilizer, especially nitrogen, could potentially improve water quality and would definitely have a positive economic effect. For example, if only 56 kilograms per hectare excess nitrogen is applied, and this is apparently quite common, net returns are reduced by $12.32 per hectare, with nitrogen costing 22.0 cents per kilogram.

The economic consequences of applying fertilizer in different forms or at different times are more difficult to assess. One must consider the prices of fertilizer for different application procedures and the

TABLE 54. PER HECTARE COSTS AND RETURNS FOR CORN UNDER CONVENTIONAL AND REDUCED TILLAGE SYSTEMS, CENTRAL GREAT PLAINS, 1979

Cost and return items	Corn: gated pipe Conventional tillage	Corn: gated pipe Reduced tillage 1/	Corn: center pivot Conventional tillage	Corn: center pivot Reduced tillage 2/
	- - - - - - - - - dollars per hectare - - - - - - - -			
Purchased inputs	139.19	139.19	139.19	176.25
Labor, except irrigation	20.66	18.43	20.66	14.01
Variable machinery costs	58.64	58.29	58.64	54.29
Fixed machinery costs	88.14	87.87	88.14	87.18
Other costs	24.93	24.76	28.05	31.26
Irrigation				
Labor	11.86	11.86	5.93	5.93
Variable machinery	37.56	35.06	88.19	75.59
Fixed machinery	96.34	96.34	131.97	131.97
Interest on operating expenses	3.29	3.11	6.25	5.41
Total irrigation	149.05	146.38	232.34	218.90
Summary				
Total cost	480.61	474.92	567.02	581.89
Gross returns	722.62	722.62	722.62	722.62
Net returns to land and management	242.01	247.70	155.60	140.73

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[1] Differs from conventional tillage in the following ways: two tandem discings are eliminated and replaced by a once-over rotary till-plant operation; one cultivation is replaced by a rotary tiller; and net water application is reduced by 2.54 centimeters.

[2] Differs from conventional tillage in the following ways: two tandem discings are eliminated and replaced by a rotary till-plant operation; additional herbicide (broadcast instead of band) is substituted for two cultivations; and net water application is reduced by 5.1 centimeters.

availability of labor and equipment. Thus, the implications of policies to modify fertilization practices are very farm-specific. For some producers, the method of fertilization which is most favorable from a water quality perspective may also be the most economical. However, other producers facing different equipment and labor availability situations might find it very difficult to comply with a given policy. Therefore, it will probably be necessary for policy makers to take a very flexible and cautious approach to this matter.

PESTICIDE USAGE

The last management practice to be discussed concerns pesticide use. There are three important managerial dimensions of the pesticide use situation: when to apply, amount to apply, and type of pesticide to use.

Programs to discourage excess pesticide applications, including applications when not needed, have positive economic effects. They also have potentially positive water quality effects, because if pesticide use is truly excessive, one can reduce it and lower costs without lowering yields (gross returns). Therefore, educational and/or regulatory programs to discourage excess pesticide use would appear to be a desirable option to improve water quality in cases where there is indeed a relationship between pesticide use and water quality.

In the case of policies to preclude or discourage the use of a particular pesticide, the economic effects could be quite adverse depending on the specific circumstances. If a close substitute exists for a pesticide which is causing water quality problems, i.e., one which can control the pest at a similar cost, the economic impact would be minimal. On the other hand, a policy which precludes the use of one or more pesticides for which good alternatives are not available could be economically disastrous. There is a potential for very adverse economic effects because of the likelihood of yield reductions. Even small yield reductions, such as 10 percent, from poor pest control would substantially effect net returns. Therefore, policies to preclude pesticide use should not be implemented without careful, situation-specific assessments of potential yield reductions, especially in cases where no close substitutes for the pesticide in question are available.

SECTION 5

CONTROL PROGRAM STRATEGIES FOR IRRIGATION RETURN FLOWS

by
J. R. Gilley and M. Twersky

Agencies and individuals have widely differing judgments regarding what constitutes best management for a specific situation. Some believe that the public water quality objective is paramount while others consider economic stability of the agricultural enterprise to be most important. A third group argues that it is possible to strike a reasonable balance between these two elements. For this reason, and because of the variation in climate, soil and current irrigation management practices used throughout the Great Plains, no single control measure or group of control measures can be thought of as best. This chapter accordingly presents an approach for choosing alternative irrigation management systems for a particular situation under varying circumstances, given the information found in Sections 1 through 4 of this manual. Presented are two illustrations of how the suggested approach might be used.

DEVELOPMENT OF A CONTROL PROGRAM

Determining whether a nonpoint pollution problem may exist and, if so, what measures may be taken to alleviate it most effectively involves a logical sequence of decisions. These decisions should result from a step-by-step procedure such as that illustrated in Figure 23 and the flow charts given in Figures 24 and 25.

The general procedure is summarized in Figure 23, the Master Flow Chart, which shows the steps required for the development of control program strategies to reduce nonpoint pollution from irrigated lands. The procedure incorporates the information gathered in response to the series of questions embodied in the flow chart for assessing deep percolation (Figure 24) and the flow chart for assessing surface runoff problems (Figure 25).

It must be remembered that these flow charts will be most effective when used as a guide by a group of specialists familiar with the local area. From the practices given in Tables 39 through 46, these specialists can develop a list of specific controls to reduce pollution resulting from irrigation return flows in the area. This type of local input is essential in arriving at the best possible choice of control practices. The final step of the Master Flow Chart, the formulation of a control program strategy based upon the most favorable environment and economic tradeoffs, is best completed by persons having knowledge of the specific land area and conditions.

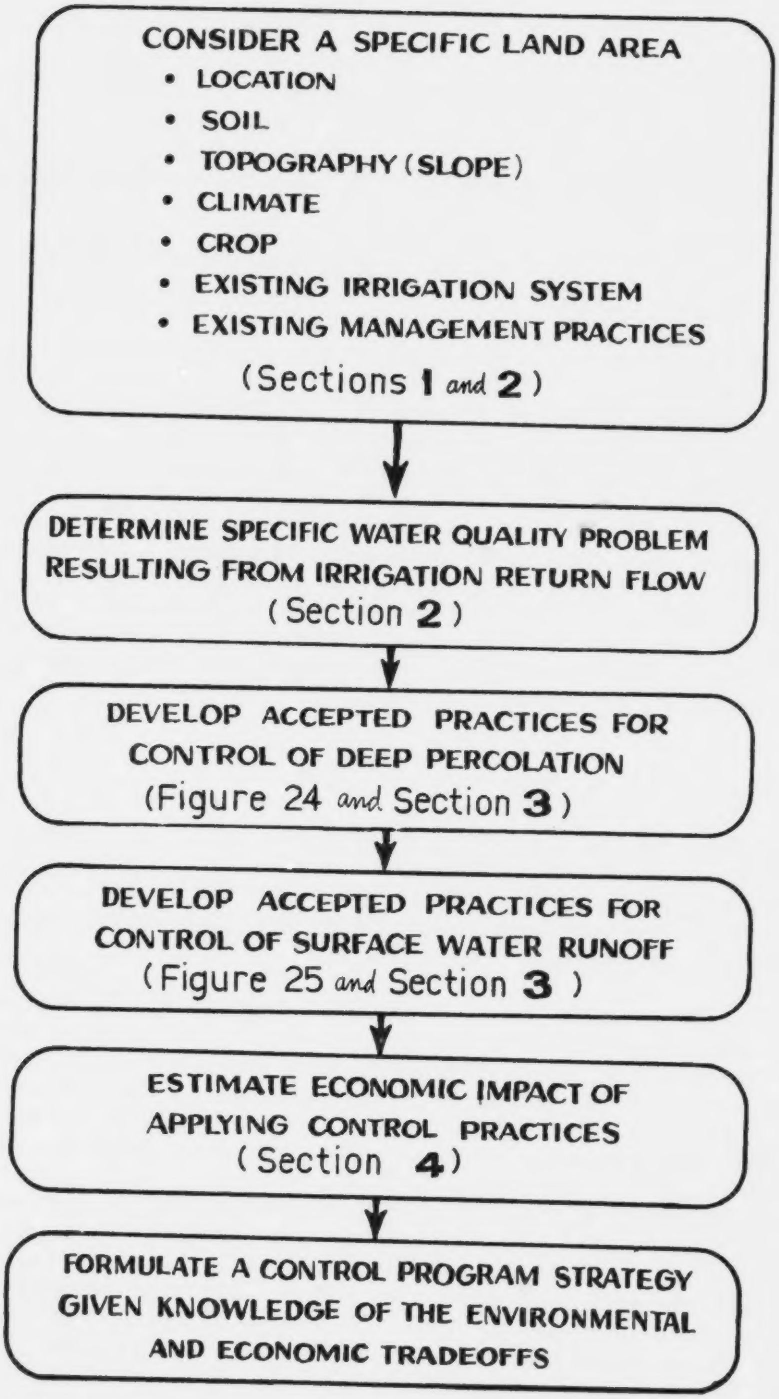
CONSIDER A SPECIFIC LAND AREA
• LOCATION
• SOIL
• TOPOGRAPHY (SLOPE)
• CLIMATE
• CROP
• EXISTING IRRIGATION SYSTEM
• EXISTING MANAGEMENT PRACTICES
(Sections 1 and 2)
DETERMINE SPECIFIC WATER QUALITY PROBLEM RESULTING FROM IRRIGATION RETURN FLOW
(Section 2)
DEVELOP ACCEPTED PRACTICES FOR CONTROL OF DEEP PERCOLATION
(Figure 24 and Section 3)
DEVELOP ACCEPTED PRACTICES FOR CONTROL OF SURFACE WATER RUNOFF
(Figure 25 and Section 3)
ESTIMATE ECONOMIC IMPACT OF APPLYING CONTROL PRACTICES
(Section 4)
FORMULATE A CONTROL PROGRAM STRATEGY GIVEN KNOWLEDGE OF THE ENVIRONMENTAL AND ECONOMIC TRADEOFFS

Figure 23. Master Flow Chart: development of control program strategies to reduce nonpoint source pollution from irrigated lands in the Great Plains.

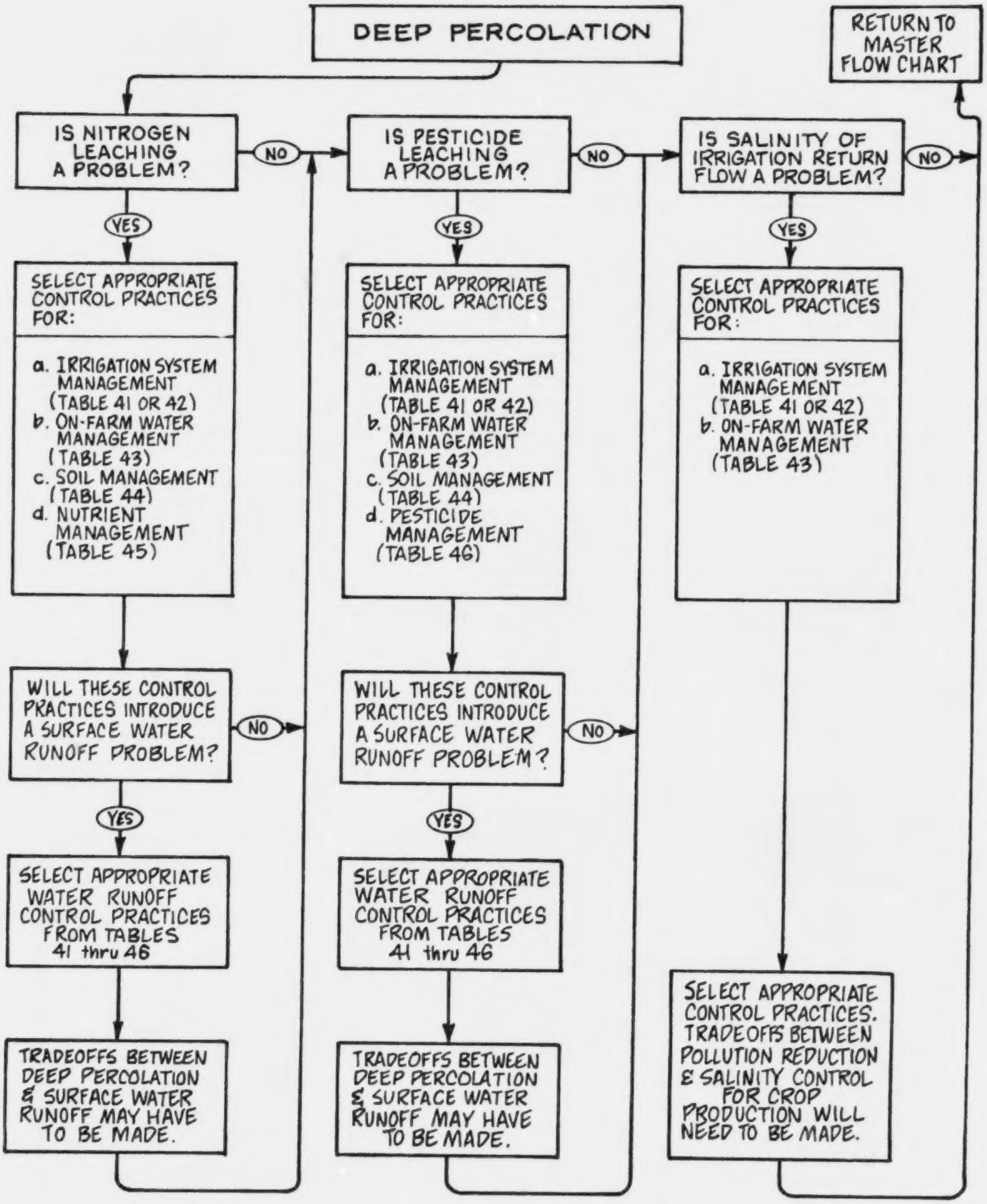
DEEP PERCOLATION
RETURN TO MASTER FLOW CHART
IS NITROGEN LEACHING A PROBLEM?
NO
IS PESTICIDE LEACHING A PROBLEM?
NO
IS SALINITY OF IRRIGATION RETURN FLOW A PROBLEM?
NO
YES
YES
YES
SELECT APPROPRIATE CONTROL PRACTICES FOR:
a. IRRIGATION SYSTEM MANAGEMENT (TABLE 41 OR 42)
b. ON-FARM WATER MANAGEMENT (TABLE 43)
c. SOIL MANAGEMENT (TABLE 44)
d. NUTRIENT MANAGEMENT (TABLE 45)
SELECT APPROPRIATE CONTROL PRACTICES FOR:
a. IRRIGATION SYSTEM MANAGEMENT (TABLE 41 OR 42)
b. ON-FARM WATER MANAGEMENT (TABLE 43)
c. SOIL MANAGEMENT (TABLE 44)
d. PESTICIDE MANAGEMENT (TABLE 46)
SELECT APPROPRIATE CONTROL PRACTICES FOR:
a. IRRIGATION SYSTEM MANAGEMENT (TABLE 41 OR 42)
b. ON-FARM WATER MANAGEMENT (TABLE 43)
WILL THESE CONTROL PRACTICES INTRODUCE A SURFACE WATER RUNOFF PROBLEM?
NO
WILL THESE CONTROL PRACTICES INTRODUCE A SURFACE WATER RUNOFF PROBLEM?
NO
YES
YES
SELECT APPROPRIATE WATER RUNOFF CONTROL PRACTICES FROM TABLES 41 thru 46
SELECT APPROPRIATE WATER RUNOFF CONTROL PRACTICES FROM TABLES 41 thru 46
TRADEOFFS BETWEEN DEEP PERCOLATION & SURFACE WATER RUNOFF MAY HAVE TO BE MADE.
TRADEOFFS BETWEEN DEEP PERCOLATION & SURFACE WATER RUNOFF MAY HAVE TO BE MADE.
SELECT APPROPRIATE CONTROL PRACTICES. TRADEOFFS BETWEEN POLLUTION REDUCTION & SALINITY CONTROL FOR CROP PRODUCTION WILL NEED TO BE MADE.

Figure 24. Flow chart for assessing deep percolation problems.

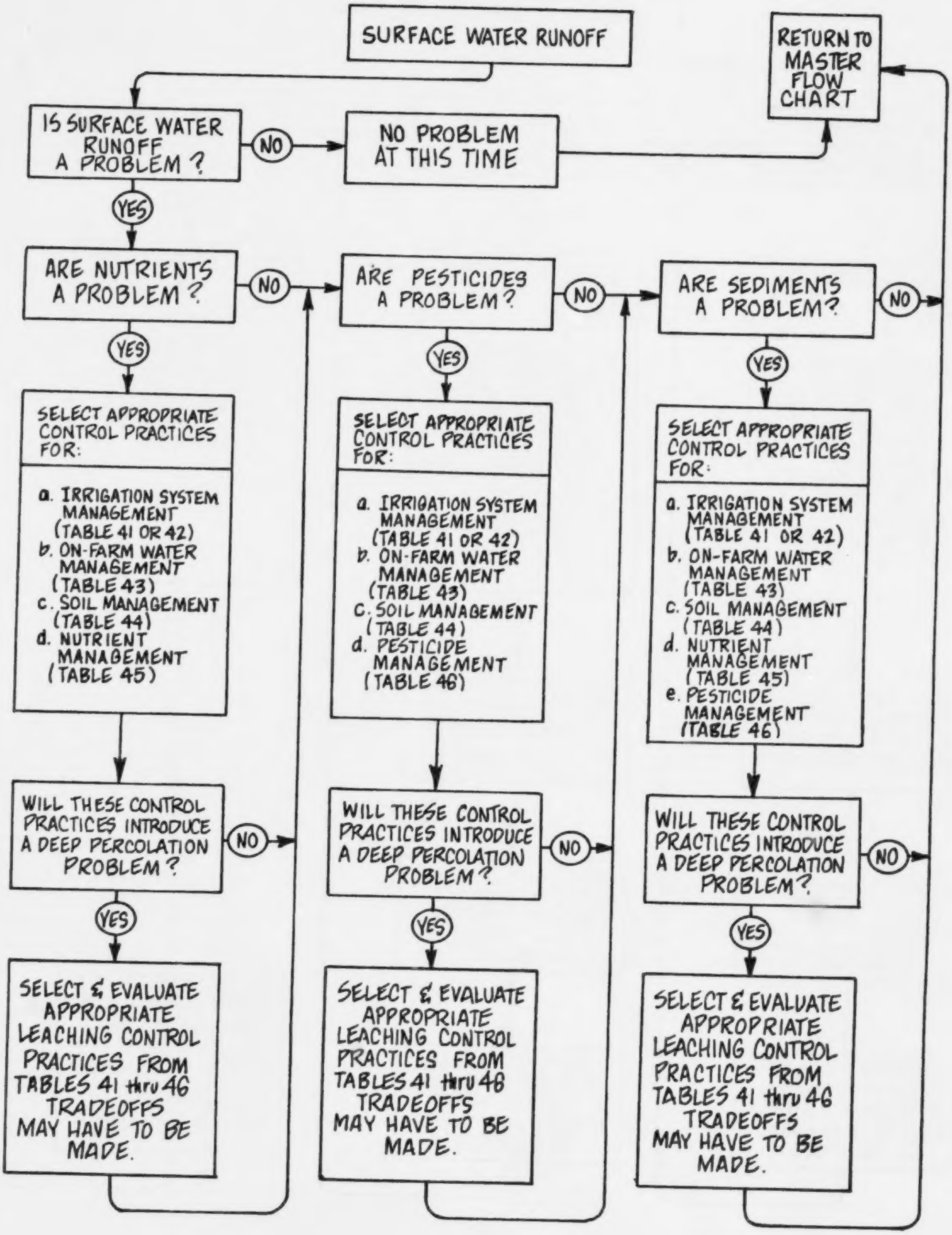
SURFACE WATER RUNOFF
IS SURFACE WATER RUNOFF A PROBLEM ?
NO
NO PROBLEM AT THIS TIME
RETURN TO MASTER FLOW CHART
YES
ARE NUTRIENTS A PROBLEM ?
ARE PESTICIDES A PROBLEM ?
ARE SEDIMENTS A PROBLEM ?
SELECT APPROPRIATE CONTROL PRACTICES FOR:
a. IRRIGATION SYSTEM MANAGEMENT (TABLE 41 OR 42)
b. ON-FARM WATER MANAGEMENT (TABLE 43)
c. SOIL MANAGEMENT (TABLE 44)
d. NUTRIENT MANAGEMENT (TABLE 45)
d. PESTICIDE MANAGEMENT (TABLE 46)
e. PESTICIDE MANAGEMENT (TABLE 46)
WILL THESE CONTROL PRACTICES INTRODUCE A DEEP PERCOLATION PROBLEM ?
SELECT & EVALUATE APPROPRIATE LEACHING CONTROL PRACTICES FROM TABLES 41 thru 46 TRADEOFFS MAY HAVE TO BE MADE.

Figure 25. Flow chart for assessing surface water runoff problems.

In some cases, an alternative control practice for deep percolation problems may introduce an increased surface water runoff problem. This situation or its opposite, when a control practice for surface water runoff causes an increased deep percolation problem, requires tradeoffs between deep percolation control and surface water runoff control. Here, compromises will be necessary. The following examples demonstrate the development of a control program using two different sets of existing circumstances.

RECOMMENDATIONS FOR TWO SITE-SPECIFIC CASES

Example of a Deep Percolation Problem

In Finney County, Kansas, a large area of sandy soils is being irrigated. There is a potential for excessive deep percolation water in this area, resulting from irrigation with center pivot sprinklers. The initial step is to obtain information for the first part of the Master Flow Chart in Figure 23. For this example, these data are:

LOCATION: Finney County, Kansas (Subarea 1103)

SOIL: Coarse-textured

SLOPE: In excess of 3 percent

CLIMATE: Precipitation is about 44 cm per year (Figure 5). Most of the precipitation occurs as rain in the spring and summer (Figure 6).

CROPS: Corn is the major row crop (85 percent) and forages constitute the remaining 15 percent.

EXISTING IRRIGATION SYSTEMS: There is extensive use of center pivots in this area.

EXISTING MANAGEMENT PRACTICE: Water from groundwater sources is applied to row crops mainly through the center pivots. Other management practices also are considered to be at a medium level.

Because of the above factors, the potential exists for contamination of groundwater supplies by nitrate-nitrogen leaching below the crop root zone. The extent of sandy soil in this area enhances the possibility of nitrate movement to the groundwater supply. Because [illegible]nagement practices in this area are considered at a medium level, it is assumed that more water than needed to meet crop needs has been applied. It is also assumed that higher-than-needed amounts of nitrogen have been applied. Excess precipitation or irrigation when crop nitrogen demands are low also increases the possibility of nitrate leaching to groundwater.

A flow chart for assessing potential deep percolation problems is given in Figure 24. Nitrate leaching has been identified as a potential problem. Several control practices can now be selected from among several irrigation management options: sprinkler irrigation system management (Table 42), on-farm water management (Table 43), soil management (Table 44) and nutrient management (Table 45).

The specific sprinkler irrigation control practices given in Table 42 for use on coarse soils with deep percolation problems offer only low to moderate pollution reduction. Because the management level has been identified as medium, it is likely that most of these practices already are used in this area. Therefore, the existing deep percolation problem will probably not be solved by any of the practices chosen from Table 42.

The on-farm water management alternatives are given in Table 43. This table shows that on coarse soils like those in this example, irrigation scheduling options can reduce the possibility of deep percolation of water. Some specific control practices suggested in Table 43, such as the installation of flow measuring devices and other automated devices, are an integral part of irrigation scheduling. Reductions of preplant irrigations and reducing irrigation amounts below crop needs are other practices which could be used. However, the economics of the latter alternative, particularly on sandy soils, must be weighed carefully before it can be recommended.

Soil management options (Table 44) offer few choices for the implementation of specific control practices to reduce pollution on coarse-textured soils. The single exception is the improvement of soil fertility. However, the soil fertility management level is actually medium, above the standard level shown on the table. Therefore, no beneficial soil management option exists for this situation.

The nutrient application methods, given in Table 45 indicate that nutrient applications through fertigation, split-application, or side-dress application offer moderate to substantial pollution reduction. One or a combination of these practices should be incorporated into the management system of this example. The fertigation option is well suited to incorporate with irrigation scheduling, especially on coarse-textured soils.

In summary, irrigation scheduling in combination with nutrient application methods are the control practices most likely to reduce deep percolation problems in this particular instance.

As shown in Figure 24, the next question to be addressed is: Will these control practices introduce a water runoff problem? On coarse-textured soils, this is highly unlikely. Proper water application also reduces the possibility of surface water runoff on the steeper slopes (6 percent and above) even though the possibility of surface runoff is low on coarse-textured soils such as those in this example. If the soil texture on a particular site is sandy loam rather than sand or loamy sand, improper water applications on steeper slopes may cause a runoff problem (Table 40). If this is the case, the information in Tables 41 through 45 must be reconsidered to include specific control practices which will reduce both deep percolation and surface water runoff. In some cases, tradeoffs between deep percolation and surface water runoff will have to be made.

From an economic viewpoint (Section 4), especially in areas with declining groundwater tables, proper application of water in amounts not exceeding crop needs can save the excessive energy costs associated with pumping and distributing the irrigation water. Also, decreased nitrate leaching leaves more nitrogen in the soil for use by the crop, thus reducing nitrogen application requirements and lowering nitrogen fertilizer costs.

In this example, irrigation scheduling and associated nutrient management practices represent a possible solution for the control of potential pollution of groundwater from IRF on sandy soils in Finney County, Kansas.

The procedure used to select the appropriate nitrate-nitrogen leaching control practices can also be applied to pesticide and salinity problems. The flow chart given in Figure 24 can be used to assess these two problems. It must be reemphasized that the important interrelationships that exist between the options presented in Tables 41 through 46 affect the choice of a particular control practice in a given situation. In most cases tradeoffs and compromises will probably be necessary.

Example of a Surface Water Runoff Problem

Surface water runoff from a furrow irrigation system without reuse can have a medium to high potential pollution rating (Table 39). Chosen for this example is a surface irrigation system in Wyoming. The management of the system indicates a higher potential for surface water runoff than deep percolation. The specifics of the situation are:

LOCATION: Goshen County, Wyoming (Subarea 1018)

SOIL: Fine silt to loam (Fine-textured)

SLOPE: 1-2 percent

CLIMATE: Precipitation is about 38 cm per year (Figure 5). Most of the precipitation occurs in the form of rain in the spring and summer (Figure 6).

CROP: Sugar beets.

EXISTING IRRIGATION SYSTEM: Furrows with siphons without reuse.

EXISTING IRRIGATION PRACTICE: Water from a surface stream is conveyed to fields in open ditches and is applied to the crop through siphon tubes. Water reuse is not part of the irrigation system. The level of management is low to medium.

On these soils with slopes in the range of 1-2 percent, surface runoff is usually larger than deep percolation losses. In this management system it is often necessary to apply more water than needed by the crop to insure water flow across the length of the field. With surface systems, the higher application of water also insures a better distribution of water in the field. Thus, surface water runoff will exceed deep percolation. Sediments are carried in this runoff as well as potential pollutants of nitrogen and phosphorus compounds adsorbed on the sediments. However, the sediments themselves constitute a major pollution problem. The flow chart for assessing surface runoff problems is given in Figure 25, and the portion devoted to sediments is used to determine the appropriate control practices for the Wyoming example.

Specific control practices for surface irrigation management are given in Table 41. For medium-textured soils some of the management alternatives that have higher pollution reduction values are: (1) installation of tail-water reuse systems; (2) matching the irrigation systems to the soil type and the slope (Table 39); and (3) reducing the length of run with reuse systems. Reduction of the length of run will require redesigning of the irrigation system and create higher labor costs. The use of a reuse system will also require capital expenditures and increase energy costs. Thus, the reduction of the length of run or the installation of reuse systems will involve some economic and environmental tradeoffs. Because it is more desirable in a surface irrigation system to have a high initial flow of water at the furrow head, it may be more desirable to install a reuse system. In cases of severe problems, it may be necessary to redesign the system or replace the system with a sprinkler system. An economic analysis of the situation must be included if these alternatives are considered.

On-farm irrigation water management options which can help alleviate sediments contained in surface water runoff are given in Table 43. For soils with surface water runoff problems the only highly rated pollution reduction option is the adoption of irrigation scheduling procedures. For a situation of this kind, the incorporation of irrigation scheduling will probably not reduce pollution as much as would the installation of a reuse system.

The soil management options are given in Table 44. Sediment basins have a high potential for reducing surface runoff problems and can be installed as part of the reuse system. Several other practices having low to moderate ratings, such as terraces, contouring, sod-based rotation and others may not be practiced under the present irrigation system. Others such as conservation tillage, grassed waterways and vegetative strips could be included to reduce surface water runoff.

An evaluation of nutrient application methods is given in Table 45. Surface runoff losses of most mobile nutrients from medium-textured soils may occur when fertigation is used in conjunction with surface irrigation and a tailwater reuse system is not employed. Soil incorporation of the fertilizer can moderately reduce the loss of nutrients with sediments and water runoff.

These various control practices may or may not introduce a deep percolation problem. If conservation tillage practices are used, it is likely that the rate at which water advances down the furrow will be slowed, requiring longer set times. This will increase the amount of water infiltrated at the upper end of the irrigation set and may increase the deep percolation loss. If a deep percolation problem is created, other appropriate practices must be chosen and tradeoffs will have to be made.

From an economic standpoint, the installation of reuse systems and a sediment basin or the switch to gated-pipe with reuse, are perhaps the best means of reducing pollution problems caused by sediments in surface water runoff. In such systems, the maximum nonerosive stream and reuse systems should be used to recapture and pump back the runoff to the irrigation system to attain the most economical use of water and energy.

It must be remembered that even the most careful water management efforts to reduce surface water runoff may be accompanied by increases in deep percolation. In such cases, tradeoffs between solutions to the two different problems will have to be made.

In this example, it should be pointed out that any change will (1) cost the grower money for capital improvements and (2) will probably increase energy requirements, especially if pumping of water (either initial application or reuse) is selected. Such investments may not pay him any additional financial return.

SUMMARY

This section has illustrated the development of control program strategies to reduce deep percolation and surface runoff in irrigation return flows. It is apparent that no single control measure or group of measures can be considered the best management system. However, the procedures illustrated can be used to identify accepted practices having higher probabilities of improving irrigation management and reducing pollution from return flows. The selection of a control program from among the accepted practices requires local input to insure local acceptability.

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APPENDIX A

COUNTY AND SUBAREA DATA

TABLE A-1. ESTIMATED PERCENTAGE OF COUNTY AREA IRRIGATED AND PERCENTAGE OF COUNTY CROPLAND IRRIGATED FOR ALL COUNTIES IN THE IRRIGATED GREAT PLAINS

				Cropland in county	
Subarea	State	County	Percent of county irrigated	Total hectares 1/ (1,000)	Percent irrigated 2/
1002	Montana	Jefferson	2.0%	22	35.0%
		Madison	4.0	59	56.0
		Beaverhead	4.0	85	73.0
		Gallatin	5.0	111	30.0
				277	
1003	Montana	Toole	0.4	50	0.9
		Liberty	0.5	227	0.7
		Chouteau	0.7	482	1.5
		Glacier	1.3	156	6.4
		Lewis & Clark	1.8	43	37.0
		Cascade	2.0	177	7.7
		Meagher	2.4	26	57.0
		Pondera	4.4	237	7.9
		Broadwater	6.0	47	39.0
		Teton	7.0	226	19.0
				1,871	
1004	Montana	Garfield	0.2	58	4.0
		Fergus	0.6	222	3.0
		Musselshell	0.8	30	13.0
		Judith Basin	1.0	122	4.0
		Golden Valley	1.2	33	12.0
		Petroleum	1.3	Not Available	--
		Wheatland	3.7	35	38.0
				500	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1005	Montana	Hill	0.5%	422	0.9%
		Valley	1.0	290	4.4
		Phillips	1.3	164	11.0
		Blaine	1.8	158	12.4
				1,034	
1006	Montana	Daniels	0.3	225	0.5
		McCone	0.3	192	1.0
		Sheridan	0.4	277	0.6
		Roosevelt	0.9	314	1.7
				1,008	
1007	Montana	Stillwater	2.0	83	11.2
		Park	2.6	51	34.5
		Sweet Grass	3.2	37	41.0
		Carbon	4.2	74	30.5
				245	
1008	Montana	Big Horn	1.6	107	19.4
	Wyoming	Hot Springs	2.5	12	100.0
		Fremont	2.8	64	100.0
		Park	3.0	58	95.0
		Washakie	3.8	21	100.0
		Big Horn	5.4	48	92.0
				310	
1009	Wyoming	Campbell	0.1	48	2.7
	Montana	Powder River	0.5	56	8.0
	Wyoming	Johnson	2.4	24	100.0
	Wyoming	Sheridan	4.3	47	61.0
				175	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county	
				Total hectares 1/ (1,000)	Percent irrigated 2/
1010	Montana	Fallon	0.4%	90	1.8%
		Wibaux	0.4	62	1.6
		Custer	0.9	56	14.7
		Prairie	1.2	Not Available	--
		Dawson	1.2	174	4.0
		Rosebud	1.3	64	26.0
		Treasure	2.7	19	36.0
		Richland	2.7	171	8.7
		Yellowstone	3.7	128	19.5
				764	
1011	N. Dakota	Billings	<0.1	48	<0.1
		Slope	<0.1	126	0.2
		Golden Valley	0.1	92	0.4
		Dunn	0.3	185	0.7
	Montana	Carter	0.5	55	8.6
	N. Dakota	McLean	0.5	378	0.7
		Mercer	0.5	127	1.2
		Williams	0.9	342	1.5
		McKenzie	1.3	213	4.3
				1,566	
1012	S. Dakota	Meade	0.2	129	1.5
	Wyoming	Weston	0.3	20	10.0
	S. Dakota	Custer	0.4	20	7.4
	Wyoming	Crook	0.4	54	5.5
	S. Dakota	Pennington	0.5	91	3.6
		Lawrence	0.7	19	7.4
		Fall River	1.0	36	13.3
	Wyoming	Niobrara	1.3	35	25.0
	S. Dakota	Butte	2.9	52	33.0
				456	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1013	N. Dakota	McIntosh	<0.1%	176	<0.1%
		Hettinger	<0.1	243	<0.1
		Sioux	<0.1	65	<0.1
		Sheridan	<0.1	158	0.1
		Logan	<0.1	157	0.1
		Adams	<0.1	159	0.1
	S. Dakota	Corson	<0.1	134	0.2
		Ziebach	<0.1	60	0.2
		Dewey	<0.1	89	<0.1
		McPherson	<0.1	151	<0.1
		Harding	<0.1	75	0.7
		Haakon	0.1	101	0.7
		Stanley	0.1	88	0.5
		Campbell	0.1	104	0.2
	N. Dakota	Stark	0.1	221	0.2
		Bowman	0.2	145	0.4
	S. Dakota	Perkins	0.2	175	0.7
		Potter	0.2	134	0.3
	N. Dakota	Grant	0.3	202	0.5
		Emmons	0.3	219	0.5
		Morton	0.3	232	0.6
		Oliver	0.4	74	1.0
	S. Dakota	Walworth	0.4	105	0.7
		Sully	0.6	136	1.2
		Hughes	0.6	76	1.6
	N. Dakota	Kidder	0.6	190	1.1
		Burleigh	1.2	227	2.3
				3,896	
1014	S. Dakota	Hyde	<0.1	79	0.1
		Brule	<0.1	106	<0.1
		Jackson	0.1	37	0.7
		Shannon	0.1	29	1.8
		Mellette	0.1	51	0.8
		Tripp	0.1	186	0.2
		Lyman	0.2	160	0.6
		Washabaugh	0.2	37	1.7

(Continued)

TABLE A-1 (Continued)

				Cropland in county	
Subarea	State	County	Percent of county irrigated	Total hectares 1/ (1,000)	Percent irrigated 2/
1014 (cont.)	S. Dakota	Gregory	0.2%	134	0.3%
		Jones	0.3	70	1.0
		Bennett	0.3	74	1.2
		Todd	0.3	64	1.4
		Buffalo	0.5	31	2.0
		Charles Mix	0.7	186	1.0
				1,244	
1015	Nebraska	Cherry	0.9	183	7.3
		Boyd	1.5	62	3.2
		Dawes	2.0	83	8.3
		Keya Paha	3.0	49	11.5
		Sheridan	2.8	145	12.3
		Sioux	3.5	32	58.0
		Rock	6.3	66	25.0
		Brown	7.5	50	47.0
		Box Butte	11.7	147	22.0
		Holt	12.2	253	30.0
				1,070	
1016	S. Dakota	Marshall	0	136	0
		Aurora	0	105	0
		Edmunds	<0.1	192	<0.1
		Faulk	<0.1	146	<0.1
		Jerauld	<0.1	75	<0.1
		Hanson	<0.1	74	<0.1
		Douglas	<0.1	83	<0.1
	N. Dakota	Wells	<0.1	280	<0.1
	S. Dakota	Clark	0.1	164	0.1
		Sanburn	0.1	88	0.2
		Hutchinson	0.1	174	0.2
		Brown	0.2	335	0.2
		Hand	0.2	188	0.3
	N. Dakota	Stutsman	0.2	396	0.3
		Eddy	0.3	115	0.4

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1016 (cont.)	S. Dakota	Davison	0.4%	82	0.5%
		Yankton	0.4	94	0.6
		Spink	0.6	282	0.9
		Beadle	0.7	203	1.0
	N. Dakota	LaMoure	0.7	247	0.9
		Foster	0.8	135	1.0
		Dickey	1.4	210	2.0
				3,804	
1017	S. Dakota	McCook	0	118	0
		Day	<0.1	200	<0.1
		Codington	<0.1	122	<0.1
		Hamlin	0.1	110	0.1
		BonHomme	0.1	111	0.1
		Miner	0.1	98	0.2
		Lincoln	0.1	123	0.1
		Deuel	0.1	110	0.2
		Kingsbury	0.1	152	0.1
		Minnehaha	0.1	160	0.2
		Lake	0.2	110	0.2
		Clay	0.5	85	0.7
		Brookings	0.5	158	0.6
		Moody	0.8	106	1.0
		Turner	1.1	136	1.3
		Union	2.0	97	2.3
	Nebraska	Dixon	2.0	92	2.7
		Knox	3.1	169	5.3
		Cedar	6.0	141	8.3
				2,398	
1018	Wyoming	Natrona	1.8	15	3/
		Converse	2.4	23	3/
	Nebraska	Garden	3.0	75	17.0
		Banner	3.6	81	8.5
	Wyoming	Platte	5.2	78	36.0
		Carbon	5.2	61	3/
		Goshen	8.0	119	39.0
		Albany	9.3	39	3/

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1018 (cont.)	Nebraska	Morrill	12.4%	94	48.0%
		Scotts Bluff	43.7	90	91.0
				675	
1019	Colorado	Denver	0.1	<1	39.0 4/
		Arapahoe	0.4	54	1.5
		Elbert	0.6	91	3.0
		Washington	2.0	305	3.0
	Nebraska	Kimball	4.3	161	4.0
	Wyoming	Laramie	4.5	129	6.5
	Nebraska	Cheyenne	4.7	226	24.0
	Colorado	Adams	7.5	194	6.5
		Logan	8.4	221	12.3
	Nebraska	Deuel	10.0	95	18.0
	Colorado	Sedgwick	10.3	91	12.0
		Weld	15.9	369	16.0
		Morgan	17.7	122	44.5
				2,058	48.0
1020	Nebraska	Grant	0.4	31	2.6
		Hooker	0.4	6	14.0
		Thomas	0.7	6	20.3
		Arthur	0.9	14	11.5
		McPherson	1.1	19	12.8
		Blaine	2.4	18	25.0
		Logan	3.0	29	15.5
		Loup	3.8	22	25.5
		Garfield	3.9	38	15.0
		Wheeler	6.2	34	27.6
		Custer	9.7	188	34.3
		Sherman	11.0	71	23.0
		Greeley	12.9	58	32.5
		Nance	14.2	66	24.4
		Valley	18.0	71	37.5
		Boone	18.3	119	27.0
		Howard	20.8	74	41.0
		Platte	25.0	135	31.7
				999	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county	
				Total hectares 1/ (1,000)	Percent irrigated 2/
1021	Nebraska	Lincoln	9.2%	167	36.0%
		Keith	12.9	104	33.0
		Buffalo	35.0	154	56.0
		Dawson	42.0	143	74.0
		Kearney	47.2	107	58.5
		Hall	53.0	94	78.0
		Merrick	53.4	84	79.0
		Phelps	55.0	109	71.0
				962	
1022	Nebraska	Wayne	2.8	98	3.3
		Lancaster	3.3	155	4.7
		Cuming	4.4	125	5.2
		Stanton	6.9	79	9.7
		Saunders	8.2	154	10.5
		Burt	9.4	103	11.3
		Madison	13.7	113	18.0
		Colfax	15.4	95	17.0
		Pierce	16.3	109	22.3
		Antelope	22.0	144	33.7
		Dodge	22.5	115	26.7
				1,290	
1025	Kansas	Norton	1.3	121	2.5
		Jewell	1.8	136	3.0
		Decatur	2.0	138	3.5
		Rawlins	2.5	162	4.2
		Cloud	3.0	125	4.5
		Clay	3.0	108	4.7
	Nebraska	Hayes	6.6	73	16.7
	Kansas	Cheyenne	7.2	153	12.6
	Colorado	Kit Carson	7.7	295	14.7
	Nebraska	Webster	9.2	73	18.9
		Furnas	10.4	109	17.8
		Frontier	10.5	88	30.0
	Kansas	Republic	10.9	132	15.3

(Continued)

TABLE A-1 (Continued)

				Cropland in county	
Subarea	State	County	Percent of county irrigated	Total hectares 1/ (1,000)	Percent irrigated 2/
1025 (cont.)	Nebraska	Dundy	12.9%	73	42.3%
	Colorado	Yuma	13.0	263	30.5
		Phillips	13.0	152	15.0
	Nebraska	Hitchcock	13.0	95	25.5
		Perkins	13.2	165	18.4
	Kansas	Thomas	14.6	226	17.9
	Nebraska	Red Willow	16.9	95	31.4
		Harlan	17.4	84	30.0
		Franklin	17.6	72	36.5
	Kansas	Sherman	19.2	179	29.4
	Nebraska	Gosper	20.5	56	44.0
		Chase	24.2	102	54.8
				3,275	
1026	Kansas	Russell	0.2	121	0.3
		Ellsworth	0.2	100	0.4
		Rooks	0.5	126	1.0
		Dickinson	0.7	160	1.0
		Lincoln	0.7	119	1.2
		Ottawa	0.9	101	1.6
		Trego	1.0	119	2.0
		Phillips	1.1	125	2.1
		Saline	1.3	106	2.3
		Smith	1.7	142	2.9
		Ellis	1.7	127	3.2
		Logan	1.9	136	3.9
	Colorado	Cheyenne	1.9	153	5.5
	Kansas	Osborne	2.1	139	3.5
		Mitchell	2.2	136	3.0
		Graham	2.2	117	4.4
		Gove	3.1	140	6.2
		Wallace	12.3	111	26.0
		Sheridan	12.7	124	24.0
				2,402	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county	
				Total hectares (1,000) 1/	Percent irrigated 2/
1027	Kansas	Washington	1.3%	147	2.0%
	Nebraska	Gage	7.6	172	10.0
		Jefferson	11.4	101	16.8
		Nuckolls	12.9	99	19.6
		Saline	19.0	112	25.3
		Butler	20.4	117	26.4
		Seward	24.0	122	29.0
		Thayer	24.4	110	33.0
		Adams	37.2	116	46.6
		Fillmore	39.6	132	44.7
		Polk	44.6	95	52.5
		Clay	44.6	112	58.7
		York	52.5	124	63.3
		Hamilton	64.5	121	74.0
				1,680	
1102	Colorado	Kiowa	0.4	192	0.8
		El Paso	0.5	42	6.8
		Lincoln	0.5	147	2.2
		Las Animas	0.6	26	27.3
		Pueblo	2.0	53	23.7
		Bent	6.4	47	53.7
		Crowley	8.8	30	60.7
		Otero	10.5	39	88.0
		Prowers	13.2	186	29.8
				762	
1103	Kansas	Kingman	1.0	133	1.8
		Ness	1.2	191	1.8
		Reno	1.3	225	1.8
		Sedgwick	1.9	186	2.6
		Rice	2.4	139	3.2
		Harvey	2.9	105	3.9
		Rush	3.0	139	4.0
		McPherson	3.3	173	4.4
		Hodgeman	4.0	115	7.9

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1103 (cont.)	Kansas	Barton	4.4%	191	5.3%
		Lane	4.4	133	6.0
		Hamilton	4.7	158	7.7
		Kiowa	5.0	105	8.9
		Greeley	6.6	141	9.4
		Stafford	7.3	142	10.5
		Pratt	7.5	138	10.3
		Pawnee	10.5	164	12.6
		Ford	11.5	205	16.0
		Edwards	15.2	114	21.4
		Kearny	20.0	129	34.5
		Scott	25.9	155	31.3
		Finney	28.0	190	49.6
		Gray	30.0	172	39.5
		Wichita	31.0	136	42.9
				3,679	
1104	Kansas	Clark	0.8	80	2.4
	Oklahoma	Harper	2.7	88	8.3
	Colorado	Baca	5.3	286	12.3
	Kansas	Meade	13.5	138	25.0
		Morton	15.0	113	25.0
		Seward	21.3	94	38.0
		Stevens	25.2	145	32.8
		Stanton	37.0	169	38.5
		Grant	45.2	110	60.5
		Haskell	56.6	127	67.0
				1,350	
1105	Oklahoma	Woods	0.4	128	1.0
		Kingfisher	2.4	155	3.6
		Major	2.9	102	7.0
				385	

(Continued)

TABLE A-1 (Continued)

Subarea	State	County	Percent of county irrigated	Cropland in county: Total hectares 1/ (1,000)	Cropland in county: Percent irrigated 2/
1106	Kansas	Barber	0.1%	101	0.4%
		Harper	0.2	148	0.3
		Comanche	0.6	74	1.8
	Oklahoma	Alfalfa	0.7	146	1.1
				469	
1108	New Mexico	Harding	0.5	14	20.3
		Mora	1.2	13	45.8
		Colfax	1.4	25	52.3
		Quay	2.9	102	21.5
				154	
1109	New Mexico	Union	1.9	36	52.0
	Texas	Oldham	3.4	40	32.5
	Oklahoma	Beaver	3.8	195	9.0
		Cimarron	10.3	174	28.0
	Texas	Hutchinson	14.3	42	77.0
	Oklahoma	Texas	16.7	301	29.7
	Texas	Dallam	21.3	131	63.0
		Hartley	23.7	88	100.0
		Ochiltree	25.0	134	43.7
		Moore	39.5	92	100.0
		Sherman	43.7	139	74.8
		Hansford	60.9	136	100.0
				1,508	
1110	Oklahoma	Dewey	0.5	91	1.5
		Blaine	0.7	124	1.3
	Texas	Hemphill	0.7	35	4.7
	Oklahoma	Woodward	1.2	86	4.5
	Texas	Roberts	2.8	19	33.4
	Oklahoma	Canadian	2.9	123	5.5
		Ellis	3.0	92	10.4
	Texas	Lipscomb	4.8	75	15.6
				645	

(Continued)

TABLE A-1 (Continued)

				Cropland in county	
Subarea	State	County	Percent of county irrigated	Total hectares 1/ (1,000)	Percent irrigated 2/
1112	Texas	Potter	3.6%	19	44.3%
		Randall	14.2	117	28.8
		Deaf Smith	39.3	206	74.5
		Swisher	50.6	162	72.5
				504	
1113	Texas	King	<0.1	15	1.0
		Foard	0.3	50	1.2
		Motley	0.5	40	3.2
		Wilbarger	0.8	106	1.8
	Oklahoma	Roger Mills	0.8	80	2.8
		Beckham	1.0	95	2.5
	Texas	Baylor	1.1	54	4.5
		Cottle	1.0	60	3.8
	Oklahoma	Kiowa	1.4	164	2.3
		Custer	1.5	137	2.8
		Grady	1.6	108	4.0
	Texas	Childress	1.7	64	5.0
		Hardeman	1.7	81	3.7
		Hall	2.3	84	6.4
	Oklahoma	Washita	2.6	176	3.8
	Texas	Wheeler	2.9	58	12.0
		Donley	2.9	37	18.4
		Collingsworth	3.3	79	9.7
	Oklahoma	Greer	3.7	78	7.8
	Texas	Armstrong	4.1	59	16.4
		Knox	4.8	84	12.6
	Oklahoma	Tillman	5.5	156	8.3
	Texas	Gray	5.8	76	18.6
	Oklahoma	Harmon	7.9	75	14.8
		Caddo	10.6	165	21.3
		Jackson	11.6	140	17.3
	Texas	Briscoe	13.2	63	47.7
				2,384	

(Continued)

TABLE A-1 (Continued)

				Cropland in county	
Subarea	State	County	Percent of county irrigated	Total hectares 1/ (1,000)	Percent irrigated 2/
1205	New Mexico	Roosevelt	8.7%	140	39.3%
	Texas	Lynn	11.0	154	17.0
	New Mexico	Curry	22.3	172	47.0
	Texas	Crosby	28.6	133	51.0
		Bailey	31.5	121	56.0
		Hockley	38.7	160	57.0
		Floyd	43.0	178	62.0
		Lubbock	52.3	190	63.8
		Lamb	66.0	183	95.0
		Castro	66.3	178	84.6
		Parmer	66.5	180	82.0
		Hale	77.6	232	84.8
				2,021	
1206	Texas	Stonewall	<0.1	41	0.5
		Kent	0.3	22	3.0
		Fisher	0.3	97	0.8
		Jones	0.4	127	0.7
		Taylor	0.5	91	1.3
		Dickens	1.3	65	5.0
		Garza	2.2	46	11.5
		Haskell	4.0	130	6.8
				619	
1208	Texas	Ector	0.2	2	20.0
		Howard	0.9	67	3.0
		Martin	2.1	92	5.5
		Andrews	2.2	52	16.6
		Midland	2.3	22	24.8
	New Mexico	Lea	3.6	35	100.0
	Texas	Dawson	8.3	173	11.2
		Yoakum	20.7	108	41.3
		Cochran	23.8	103	46.8
		Terry	24.3	178	32.0
		Gaines	42.0	220	73.7
				1,052	

(Continued)

TABLE A-1 (Continued)

[1] Based on figures from the 1974 Census of Agriculture (for each of the ten Great Plains states), U.S. Dept. of Commerce, Bureau of the Census, Washington, D.C.

[2] Based on 1976 and 1977 figures for irrigated hectares (sources referenced in Section 1), divided by figures for total cropland obtained from 1974 Census of Agriculture (for each of the ten Great Plains states), Dept. of Commerce, Bureau of the Census, Washington, D.C.

[3] In the case of these four Wyoming counties, the 1976 figures for irrigated hectares were larger than the 1974 figures for total cropland. Based on this information, an accurate percent of total cropland which is irrigated could not be determined.

[4] Of all the counties listed, Denver County had the lowest number of irrigated hectares--only 70. Because the county is the site of the city of Denver, however, there is also little total cropland.

APPENDIX A

TABLE A-2. SUBAREAS, ALL OR PART OF WHICH ARE INCLUDED IN THE IRRIGATED GREAT PLAINS, AND THE DRAINAGE BASIN EACH REPRESENTS 1/

Subarea number	Drainage basin it represents
1002	Missouri River Headwaters
1003	Missouri-Marias
1004	Missouri-Musselshell
1005	Milk
1006	Missouri-Poplar
1007	Upper Yellowstone
1008	Bighorn
1009	Tongue-Powder
1010	Lower Yellowstone
1011	Missouri-Little Missouri
1012	Cheyenne
1013	Missouri-Oahe
1014	Missouri-White
1015	Niobrara
1016	James
1017	Missouri-Big Sioux
1018	North Platte
1019	South Platte
1020	Loup
1021	Platte
1022	Elkhorn

(Continued)

TABLE A-2 (Continued)

Subarea number	Drainage basin it represents
1025	Republican
1026	Smoky Hill
1027	Upper Kansas (Big Blue)
1102	Upper Arkansas
1103	Arkansas in Kansas
1104	Upper Cimarron
1105	Lower Cimarron
1106	Arkansas-Keystone
1108	Upper Canadian
1109	Canadian in Texas
1110	Lower Canadian
1112	Red River Headwaters
1113	Red-Washita
1205	Brazos Headwaters
1206	Middle Brazos
1208	Colorado (Texas) Headwaters

1/ From U.S. Water Resources Council, 1970.

APPENDIX B

COMMONLY-USED HERBICIDES, INSECTICIDES, AND MITICIDES

TABLE B-1. HERBICIDES COMMONLY USED IN FIVE CROPS IN THE GREAT PLAINS

Herbicide		Crop									
Common Name	Trade Name	Alfalfa	Corn	Cotton	Sorghum	Soybeans	Chemical Class 1/	Transport Mode 2/	Acute Oral Toxicity Class 3/	Mobility Class 4/	Average Persistence 5/
Alachlor	Lasso		X 6/			X 6/	AM	SW	3	3	2
Atrazine	AAtrex, Atrazine		X 6/		X 6/		TZ	SW	3	3	4
Benefin	Balan	X					NA	S	3	1	3
Bentazon	Basagran		X			X	DZ	W	3	5	1
Bifenox	Modown				X	X	AR	S	3	1	2
Butylate	Sutan		X 6/				CB	S	3	3	2
Cacodylic acid	various			X			AS	S	3	1	-
Chloramben	Amiben		X				AR	W	3	5	2
Chlorpropham	Chem-Hoe, Furlow	X					CB	SW	3	3	2
Cyanazine	Bladex		X 6/		X		TZ	SW	2	3	2
Dalapon	Dowpon		X	X	X	X	AL	W	4	5	1
Dicamba	Banvel		X 6/		X		AR	W	3	5	2
Dinitramine	Cobex			X		X	NA	S	3	1	3
Dinoseb	Premerge, Dow General	X					PH	SW	1	4	1
Diphenamid	Dymid, Enide			X			AM	W	3	5	2
Diuron	Karmex	X		X			UR	S	3	2	4
DSMA	various			X 6/			AS	S	3	2	-
EPTC	Eptam, Eradicane	X	X 6/	X			CB	SW	3	4	1
Fluometuron	Cotoran, Lanex			X 6/			UR	SW	4	4	2
Glyphosate	Roundup		X		X	X	AL	S	3	1	1
Linuron	Lorox		X	X	X	X	UR	S	3	2	2

(Continued)

TABLE B-1 (continued)

Herbicide		Crop					Chemical Class 1/	Transport Mode 2/	Acute Oral Toxicity Class 3/	Mobility Class 4/	Average Persistence 5/
Common Name	Trade Name	Alfalfa	Corn	Cotton	Sorghum	Soybeans					
Methazole	Probe			X			--	S	3	2	2
Metolachlor	Dual		X 6/				AM	SW	3	3	2
Metribuzin	Lexone, Sencor	X				X 6/	TZ	W	3	4	2
MSMA	various			X 6/			AS	S	3	1	-
Oryzalin	Surflan					X	AM	S	4	2	3
Paraquat	Paraquat		X	X	X	X	CT	S	2	1	5
Pendimethalin	Prowl		X	X		X	NA	S	3	1	3
Perfluidone	Destun			X			--	W	3	4	2
Profluralin	Tolban	X		X		X	NA	S	3	1	3
Prometryn	Caparol			X			TZ	S	3	3	2
Propachlor	Bexton, Ramrod		X		X 6/		AM	W	3	4	1
Propazine	Milogard				X 6/		TZ	S	3	2	4
Simazine	Princep	X	X				TZ	S	3	2	4
Terbacil	Sinbar	X					DZ	W	3	4	5
Terbutryn	Igran				X		TZ	SW	3	3	2
Trifluralin	Treflan			X 6/		X 6/	NA	S	3	1	3
2,4-D	various		X 6/		X 6/		PO	SW	2	4	1
2,4-DB	Butoxone, Butyrac	X				X	PO	S	2	4	1
Vernolate	Vernam					X	CB	SW	3	3	1

(Continued)

TABLE B-1 (continued)

1/ Chemical type designations: AL, aliphatic acids; AM, amides and anilides; AR, aromatic acids and esters; AS, arsenicals; CB, carbamates and thiocarbamates; CT, cationics; DZ, diazines; NA, nitroanilines; NT, nitriles; PH, phenols and dicarboxylic acids; PO, phenoxy compounds; TZ, triazines and triazoles; UR, ureas.

2/ Where movement of herbicides in runoff from treated fields occurs, S denotes those chemicals that will most likely move primarily with the sediment, W denotes those that will most likely move primarily with the water, and SW denotes those that will most likely move with both sediment and water.

3/ Acute oral LD_{50} classes:

1 - less than 50 mg/kg (most toxic)
2 - 50 to 500 mg/kg
3 - 500 to 5,000 mg/kg
4 - less than 5,000 mg/kg (least toxic)

4/ Mobility Class:
1 - Immobile
3 - Slightly mobile
5 - Mobile

5/ Persistence Class - Residual Life
1. 0 - 2 months
2. 2 - 6 months
3. 6 - 12 months
4. 1 - 3 years
5. over 3 years

6/ Represents major use.

TABLE B-2. INSECTICIDES AND MITICIDES COMMONLY USED IN FIVE CROPS IN THE GREAT PLAINS

Insecticide		Crop					Chemical Class[1]	Transport Mode[2]	Acute Oral Toxicity Class[3]
Common Name	Trade Name	Alfalfa	Corn	Cotton	Sorghum	Soybeans			
Aldicarb	Temik			X [4]			CB	W	1
Azinphos methyl	Guthion	X		X	X		OP	S	1
Carbaryl	Sevin	X	X [4]	X	X [4]	X [4]	CB	SW	2
Carbofuran	Furadan	X	X [4]	X			CB	W	1
Carbophenothion	Trithion	X	X	X	X	X	OP	S	1
Chlordimeform	Galecron			X			N	W	2
Chlorobenzilate	Acaraben			X			OCL	S	3
Chlorpyrifos	Lorsban		X	X			OP	U	2
Demeton	Systox	X		X	X		OP	W	1
Diazinon	Spectracide	X [4]	X	X	X	X	OP	SW	2
Dicrotophos	Bidrin			X			OP	W	1
Dicofol	Kelthane			X			OCL	S	3
Dimethoate	Cygon	X		X	X [4]		OP	W	2
Disulfoton	Di-Syston	X	X	X	X [4]	X	OP	S	1
EPN	EPN		X	X [4]			OP	S	1
Endosulfan	Thiodan	X		X			OCL	S	1
Endrin	Endrin			X			OCL	S	1
Ethoprop	Mocap		X [4]				OP	U	2
Fonophos	Dyfonate		X [4]				OP	S	1

(Continued)

TABLE B-2 (continued)

Insecticide		Crop					Chemical Class [1]	Transport Mode [2]	Acute Oral Toxicity Class [3]
Common Name	Trade Name	Alfalfa	Corn	Cotton	Sorghum	Soybeans			
--------	Landrin		X				CB	SW	2
Malathion	Malathion	X [4]	X	X	X	X	OP	W	2
Methyl parathion	Methyl parathion	X	X	X [4]	X	X	OP	SW	1
Methidathion	Supracide	X [4]		X			OP	U	1
Methomyl	Lannate	X	X				CB	U	1
Methoxychlor	Marlate	X [4]	X				OCL	S	4
Mevinphos	Phosdrin	X	X		X		OP	W	1
Naled	Dibrom	X		X			OP	S	2
Parathion	Parathion	X	X	X	X [4]	X	OP	S	1
Phorate	Thimet	X	X [4]	X	X		OP	SW	1
Phosmet	Imidan	X					OP	S	2
Phosphamidon	Dimecron			X			OP	W	1
Propargite	Omite			X			S	U	3
Terbufos	Counter		X [4]				OP	U	1
Toxaphene	Toxaphene	X	X	X [4]	X [4]	X [4]	OCL	S	2
Trichlorfon	Dylox	X		X		X [4]	OP	W	2

(Continued)

TABLE B-2 (continued)

1/ Chemical type designations: CB, carbamates; N, miscellaneous nitrogenous compounds; O, cyclic oxygen compounds; OCL, organochlorines; OP, organophosphorus compounds; PY, synthetic pyrethrin; S, aromatic and cyclic sulfur compounds.

2/ Where movement of insecticides in runoff from treated fields occurs, S, denotes those chemicals that will most likely move primarily with the sediments, W, denotes those that will most likely move primarily with the water, SW, denotes those that will most likely move with both sediment and water, and U, denotes those whose predominant mode of transport cannot be predicted because properties are unknown.

3/ Acute oral LD_{50} classes:

1 - less than 50 mg/kg (most toxic)
2 - 50 to 500 mg/kg
3 - 500 to 5,000 mg/kg
4 - less than 5,000 mg/kg (least toxic)

4/ Represents major use.

APPENDIX C

BASE DATA AND PROCEDURES FOR THE CROP BUDGETS AND IRRIGATION COST ESTIMATES

CROP BUDGETING PROCEDURES

The model farm budgets were developed with the aid of a computerized crop budgeting program, which is available on the Agricultural Computer Network (AGNET) at the University of Nebraska-Lincoln. This program automates many of the tedious calculations which are required in preparing crop budgets.

A benchmark, or "typical", farm unit was selected for the Southern and Central Plains areas. Each benchmark farm represents the farming or ranching operation of an "above average" operator in the area. The selection of a benchmark farm directly affects the production costs shown in the crop enterprise budgets. The relative level of management is reflected in the cultural practices employed, fertilization rates, and expected yields. The inventory of machinery, the size of each machine, and the amount of time each machine is used annually determine the fixed machinery cost per hectare. Thus, the size of the farm, the cropping plan, and the machinery inventory are important determinants of crop production costs. A description of the benchmark farm is in the text and the machinery inventories are shown in Table C-1.

Current prices for the machinery used on each benchmark farm were collected from major machinery manufacturing companies. Cost factors, based largely on information in the Agricultural Engineer's Yearbook, were applied to determine repair rates, annual fixed costs, and accomplishment rates. Fuel consumption factors were based on Nebraska tractor test data.

Irrigation costs were calculated using current prices of irrigation equipment, engineering performance standards, and typical water application rates. A detailed description of the irrigation cost procedures is discussed later in this appendix.

Tillage practices, plant population, yields, custom operations, and other practices which are typical in the area of the benchmark farm were based on farm record data, workshops with growers, consultation with extension specialists in other disciplines, and the judgment of farm management specialists.

Yields shown in the budgets are estimates of those which an above-average producer might average over several years, including years of low yields due to drouth, hail, insect damage, etc. Consequently, no allowance

TABLE C-1. MACHINERY INVENTORIES FOR THE CENTRAL AND SOUTHERN PLAINS FARM SITUATIONS

Central Plains

- 130 hp diesel tractor
- 90 hp diesel tractor
- Old usable tractor (no market value)
- Truck, 350 bushel grain box
- Pickup, 3/4 ton
- Tandem disc, 21'
- Corn machinery, 30" spacing
- Shredder, 6 row
- Anhydrous applicator, 6 row
- Planter, 6 row
- Cultivator-tiller, 6 row
- Combine, 6 row cornhead
  20' grain platform
- Wagon, 425 bushel
- Auger, 62' 8"
- Dryer, cont. flow, 350 bushel/hr.
  remove 8 points moisture
- Wet corn handling bin, 3300 bushel
- Chisel sweeps, 20'
- Field conditioner, 32'
- Grain drill, 16' 10"
- Irrigation equipment
  - Pivot sprinkler, diesel
  - Gravity wells, 2 diesel
    - reuse pits, pumps, and return pipe
  - Gated, conveyor, and reuse pipe
    - Layout beginning of season and pick up at end of season
- Pipe
- Bale loader

Southern Plains

- 110 hp diesel tractor
- 90 hp diesel tractor
- 60 hp gasoline tractor
- 40 hp gasoline tractor
- Pickup, 1/2 ton
- Shredder, 4 row
- Tandem disc, 15'
- Moldboard plow, 6 bottom
- Packer, 15'
- Chisel, 15'
- Sprayer, 15'
- Corn-Grain Sorghum Equipment,
  - 8 row lister
  - Rolling cultivator
  - Bed planter
  - Sand fighter
- Cotton Equipment, 6 row
  - Box float
  - Lister
  - Rolling cultivator
  - Bed planter
- Wheat Equipment
  - Offset disc, 15'
  - Grain drill, 20'
- Irrigation Equipment
  - Ditcher
- Siphon tubes

was made for the expense of crop insurance, or the income from crop insurance proceeds.

Labor requirements were calculated from machinery accomplishment rates, with an additional 20 percent added for "non-field" time required for crop production, such as getting machinery ready, driving to and from fields, hauling fertilizer, buying seed, chemicals, and other supplies.

Interest on operating expenses was charged at 9.5 percent for the portion of the year that cash was tied up.

Farm overhead expenses were estimated to be 5 percent of other cash expenses based on past studies of farm records. Overhead expenses include items which are normally not allocated to individual farm enterprises, yet which are necessary to keep an ongoing business running. These include pickup expense, farm share of car expense, farm publications, unallocated farm utilities, cost of attending farm meetings, income tax preparation expense, etc.

Production input prices were estimated based on prevailing market conditions (Table C-2).

TABLE C-2. PRODUCTION INPUT PRICES USED IN ESTIMATION OF CROP BUDGETS

Fertilizer	
N-Anhydrous	$ 0.22/kilogram (kg.)
Liquid or dry	0.44/kg.
P_2O_5	0.44/kg.
K_2O	0.22/kg.
18-46-0 starter	243.56/tonne
10-34-0 liquid	209.82/tonne
Herbicides	
Corn and sorghum	12.35/hectare (ha.)
Soybean	13.59/ha.
Aerial spray 2,4-D	
Corn or sorghum	9.27/ha.
Pastures	14.83/ha.
Insecticides	
Corn (rootworm) (13.96/ha. for 101.6 cm rows)	19.77/ha.
Aerial spray	
Rootworm beetle	11.12/ha.
Alfalfa weevil or greenbug	11.12/ha.
Western bean cutworm/armyworm	17.30/ha.
Spider mites or grasshoppers	12.35/ha.
Seed	
Corn--single cross (80,000 kernels per bag)	51.00/bag
Sorghum	0.01/kg.
Alfalfa	2.25/kg.
Wheat	0.15/kg.
Interest	9.5 percent
Labor	
Machinery operations	4.00/hour
All other	3.00/hour

(Continued)

TABLE C-2. (Continued)

Energy	
Electricity	0.053/kwh
Natural gas (Central Plains)	50.00/1000 cu. meters
Natural gas (Southern Plains)	62.50/1000 cu. meters
Propane	0.09/liter
Diesel	.13/liter

Estimated Irrigation Costs

Irrigation costs were estimated with the use of AGNET's "pump" computer program at the University of Nebraska-Lincoln. Energy prices used in the cost computation were 1979 expected prices. The irrigation equipment, well drilling, and land-shaping costs used in the budgets were collected by a telephone survey of selected dealers in August, 1978 (Tables C-3 and C-4).

TABLE C-3. INVESTMENT COSTS FOR SELECTED IRRIGATION SYSTEMS, CENTRAL PLAINS [1/]

	Type of irrigation system			
Item	Gated pipe without reuse pits	Gated pipe with reuse pits	Automatic gated pipe	Center pivot sprinkler
Well	$2,800	$2,800	$2,800	$2,800
Pump	4,400	4,400	4,400	5,000
Power unit	5,900	5,900	5,900	12,000
Gearhead	1,200	1,200	1,200	2,600
Fuel tank	500	500	500	500
Pipe, main or gated	9,100	9,100	16,250	1,000
Leveling or sloping	19,500	19,500	19,500	1,950
Reuse system	0	4,200	4,200	0
Sprinkler system	0	0	0	28,000
Electric generator	0	0	0	1,000

[1/] The Central Plains investment costs assume that a 3.04 cubic meters per minute well with 30.5 meters of lift is used for all irrigation systems.

TABLE C-4. INVESTMENT COSTS FOR SELECTED IRRIGATION SYSTEMS, SOUTHERN PLAINS [1]

Item	Type of irrigation system			
	Without reuse pits	With reuse pits	Automatic gated pipe	Center pivot sprinkler
Well	$ 5,300	$ 5,300	$ 5,300	$ 7,950
Pump	7,925	7,925	7,925	13,088
Power unit	2,725	2,725	2,725	8,175
Gearhead	1,700	1,700	1,700	4,350
Pipe, main or gated	500	500	10,625	1,500
Leveling or sloping	2,250	2,250	2,250	225
Reuse system	0	4,200	4,200	0
Sprinkler system	0	0	0	28,000
Electric generator	0	0	0	1,500
Other	0	0	0	500

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[1] The Southern Plains investment costs assume a single 2.47 cubic meters per minute well for three gravity irrigated systems and one and one-half wells for the center pivot system. The lift is 68.6 meters for all four systems.

Fixed irrigation costs (depreciation, interest on the investment, and insurance) were calculated from the investment costs using the following factors;

Depreciation rates:

	Percent	Years of life
Wells	4.0	25
Power units		
Nat. gas or propane	11.1	9
Diesel (w/o reuse)	9.09	11
Diesel (with reuse)	12.5	8
Gearhead	5.56	18
Fuel tanks and lines	5.0	20
Pipe	6.67	15
Sprinkler system	6.67	15
Reuse system	4.0	25

Interest was figured at 4.5 percent of original investment on all items except leveling. (This is equivalent to 9.0 percent on the average undepreciated balance). Interest and taxes on the investment in leveling were figured at 7 percent.

Variable irrigation costs (energy, lubrication, repairs, and service labor) were calculated using engineering formulas and anticipated 1979 energy prices. Power units were assumed to be operating at 85 percent of the Nebraska performance standards.

APPENDIX D

METRIC CONVERSIONS

CONVERSION TABLES

To compute the United States Customary (or English) system equivalent of a quantity given in metric units requires the use of an appropriate conversion factor. Conversion factors for units of length, area, volume, weight, and concentration used in this manual are presented in the first five tables which follow. Table D-6 presents the conversion factors for several special unit combinations deemed helpful for the reader.

TABLE D-1. UNIT CONVERSIONS FOR LENGTH

To convert from: Metric unit	Symbol	Multiply by: Conversion factor	To obtain: English unit
centimeter	cm	0.394	inch
meter	m	39.4	inch
"	m	3.28	foot
"	m	1.09	yard
kilometer	km	0.621	mile

TABLE D-2. UNIT CONVERSIONS FOR AREA

To convert from: Metric unit	Symbol	Multiply by: Conversion factor	To obtain: English unit
square centimeter	cm^2	0.155	square inch
square meter	m^2	1,550	square inch
" "	m^2	10.8	square feet
" "	m^2	1.20	square yard
square kilometer	km^2	0.386	square mile [a]
square kilometer	km^2	247	acre
hectare [b]	ha	2.47	acre

[a] 1 square mile = 640 acres.

[b] A hectare is actually 1 square hectometer (hm^2).
$1\ hm^2 = 10,000\ m^2 = 0.01\ km^2$.

TABLE D-3. UNIT CONVERSIONS FOR VOLUME

To convert from: Metric unit	Symbol	Multiply by: Conversion factor	To obtain: English unit
milliliter	mL [a]	0.0338	fluid ounce
"	mL	0.0610	cubic inch
liter [b]	L	1.06	quart (liquid) [c]
"	L	0.264	gallon [d]
"	L	0.0284	bushel [e]
"	L	61.0	cubic inch
"	L	0.0353	cubic foot
cubic meter	m^3	35.3	cubic foot
" "	m^3	28.4	bushel
hectare-centimeter	ha·cm	0.973	acre-inch
hectare-meter	ha·m	8.11	acre-foot

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[a] To prevent confusion between the lower-case letter "l" and the number "1", the word 'liter' can be either spelled out or represented by an upper-case "L", as done here.

[b] Liter is a special name for the cubic decimeter (dm^3).

$1\ L = 1\ dm^3 = .001\ m^3$
$1\ mL = 1\ cm^3$

[c] 1 quart (liquid) = 0.86 quart (dry).

[d] The conversion is for the U.S. gallon:

1 gallon = 4 quarts (liquid).

[e] The conversion is for the U.S. bushel:

1 bushel = 4 pecks = 32 quarts (dry).

TABLE D-4. UNIT CONVERSIONS FOR MASS TO WEIGHT [a]

To convert from: Metric unit	Symbol	Multiply by: Conversion factor	To obtain: English unit
gram	g	0.0353	ounce
kilogram	kg	2.20	pound
tonne [b]	t	1.10	ton [c]
"	t	2,200	pound

[a] These mass-to-weight conversion factors are for the normally-expected elevations and locations.

[b] The tonne, or metric ton, is equal to 1,000 kilograms.

[c] The ton is called the short or net ton and is equal to 2,000 pounds. This is distinguished from the long ton of 2,240 pounds.

TABLE D-5. CONCENTRATION IN WATER

To convert from:	Abbreviation	Multiply by: Conversion factor	To obtain:
Parts per million	ppm	1.0	milligrams/liter
" " "	ppm	0.1	kilograms/hectare-centimeter
" " "	ppm	2.72	pounds/acre-foot
Parts per billion	ppb	1.0	micrograms/liter
" " "	ppb	0.1	grams/hectare-centimeter
" " "	ppb	0.043	ounces/acre-foot

TABLE D-6. UNIT CONVERSIONS FOR SPECIAL COMBINATIONS

To convert from: Metric unit	Symbol	Multiply by: Conversion factor	To obtain: English unit
tonne/hectare	t/ha	0.446	tons/acre
kilogram/hectare	kg/ha	0.892	pounds/acre
kilogram/tonne	kg/t	2.00	pounds/ton

Many publications dealing with the metric system are available. The following are only a few of those that may be helpful to the reader who wishes to pursue the subject further:

Metric Manual. 1975. J. J. Keller and Associates, Inc., Neenah, Wisconsin.

SI Metric Handbook. 1977. John L. Feirer, The Metric Company; Charles Scribner's Sons, New York.

The International System of Units. 1977. National Bureau of Standards Publication 330, U.S. Department of Commerce, Washington, D.C.

The Metric Encyclopedia. 1975. A. L. LeMaraic and J. P. Earamella, ed., Abbey Books, Metric Media Book Publishers; Somers, New York.

System International d'Unites, Metric Measurement in Water Resources Engineering. 1976. Peter C. Klingeman. The Universities Council on Water Resources, Lincoln, Nebraska.